



## **Mechanical and Thermal Properties of Advanced Ceramics for Gun Barrel Applications**

**by Jeffrey J. Swab, Andrew A. Wereszczak, Jason Tice, Russ Caspe,  
Reuben H. Kraft, and Jane W. Adams**

**ARL-TR-3417**

**February 2005**

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**ARL-TR-3417****February 2005**

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Weapons and Materials Research Directorate, ARL**

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| 14. ABSTRACT<br><p>Eight commercially available ceramic materials were procured and evaluated for potential application as gun barrel liners. These materials included an alumina, zirconia, and SiAlON, as well as three silicon carbides and two silicon nitrides. Preliminary evaluation determined the strength, fracture toughness, Vickers hardness, thermal conductivity, specific heat, and linear coefficient of thermal expansion. An uncensored Weibull analysis was performed on all of the strength data. These databases were developed for use in the probabilistic modeling and design efforts of the program to predict performance, identify optimum gun barrel designs, and to rank and down select ceramics for further evaluation.</p>   |                             |                              |  |   |   |
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## **Foreword**

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Jason Tice and Rueben Kraft performed this work while undergraduates at the University of Maryland Baltimore County and with support by an appointment to the Research Participation Program of the U.S. Army Research Laboratory (ARL) administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and ARL.

Russ Caspe performed this work while an undergraduate student in the Department of Ceramic and Materials Engineering, Rutgers University, Piscataway, NJ, with support from the ARL Materials Center of Excellence at Rutgers University, High Fidelity Design, and Processing of Advanced Armor Ceramics.

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- Steve Goodrich at the University of Dayton Research Institute for conducting the uniaxial tensile and sector flexure strength tests.
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- Netzsch Instruments, Billerica, MA, for conducting the thermal conductivity, heat capacity, and coefficient of thermal expansion experiments for each material.
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## 1. Background

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The U.S. Army Research Laboratory is currently assessing the feasibility of ceramic gun barrels in an attempt to provide a significant increase in barrel life, a reduction in weight (primarily for smaller caliber systems), and enable the use of higher energetic propellants. This investigation spans a range of calibers from the 5.56-mm rifle to the 155-mm artillery system. The steel gun barrels currently used by the Army for these systems have a short lifecycle and cannot withstand many of the higher energy propellants that are currently available or under development. It is anticipated that ceramic gun barrel liners will provide a 50% increase in barrel life with sustained accuracy for direct and indirect fire, enable a 20% increase in muzzle kinetic energy for direct fire, and provide a 5%–25% weight reduction (per unit length of barrel) owing to the combination of superior wear resistance, high temperature capability, and relatively low density that are inherent to ceramic materials. The development of a ceramic gun barrel will reduce maintenance costs while serving as an enabling technology for the use of higher energy propellants.

The program to examine ceramic materials for gun barrel applications includes material evaluation of commercially-available advanced ceramics, probabilistic modeling to develop an optimized ceramic gun barrel design, erosion testing to simulate the gun barrel environment, extensive examination of sheathing technology to provide the necessary hoop and axial confinement, and finally, ballistic testing of a barrel segment. This report presents a summary of the mechanical and thermal property data generated on eight advanced ceramic materials.

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## 2. Materials Information

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The materials examined in this study are all commercially-available ceramics that include two silicon nitrides, a SiAlON, three silicon carbides, one alumina, and one zirconia.<sup>\*</sup> Traditional sintering methods were used to fabricate all materials, with the exception of the SiAlON (STK4), which was subjected to a post sintering hot isostatic pressing process. Table 1 lists the materials evaluated. The microstructure of each material is shown in figures 1–8. In some cases, it was necessary to thermally or chemically etch a material to highlight the microstructure. If a material required etching, the etchant is

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<sup>\*</sup> Certain commercial materials or equipment are identified in this report to adequately specify the experimental procedure. This in no way implies endorsement of materials or equipment by the U.S. Army Research Laboratory, or that these are necessarily the best for these purposes.

noted in the figure caption. Each material was ordered from the respective vendors in the three geometries shown in figure 9. Circumferential machining and a minimum surface finish of 0.8  $\mu\text{m}$  on the outer diameter of all tubes (geometry B) were requested of each vendor.

Table 1. Material information.

| Material                       | Vendor       | Vendor Code         | ARL Code | Vintage | Density<br>(g/cm <sup>3</sup> ) |
|--------------------------------|--------------|---------------------|----------|---------|---------------------------------|
| Al <sub>2</sub> O <sub>3</sub> | CoorsTek     | AD995               | ALOX     | 2001    | 3.8                             |
| ZrO <sub>2</sub>               | CoorsTek     | Ce-TZP              | ZRO2     | 2001    | 6.1                             |
| SiC                            | Saint-Gobain | Enhanced hexoloy SA | SCEH     | 2001    | 3.1                             |
| SiC                            | Saint-Gobain | LPS hexoloy SA      | SCLH     | 2001    | 3.1                             |
| SiC                            | Ceradyne     | Ceralloy<br>146-5S  | SC46     | 2001    | 3.1                             |
| Si <sub>3</sub> N <sub>4</sub> | Ceradyne     | Ceralloy<br>147-31N | SN47     | 2001    | 3.2                             |
| SiAlON                         | Kennametal   | TK4                 | STK4     | 2001    | 3.4                             |
| Si <sub>3</sub> N <sub>4</sub> | Kyocera      | SN235P              | SN5P     | 2002    | 3.2                             |

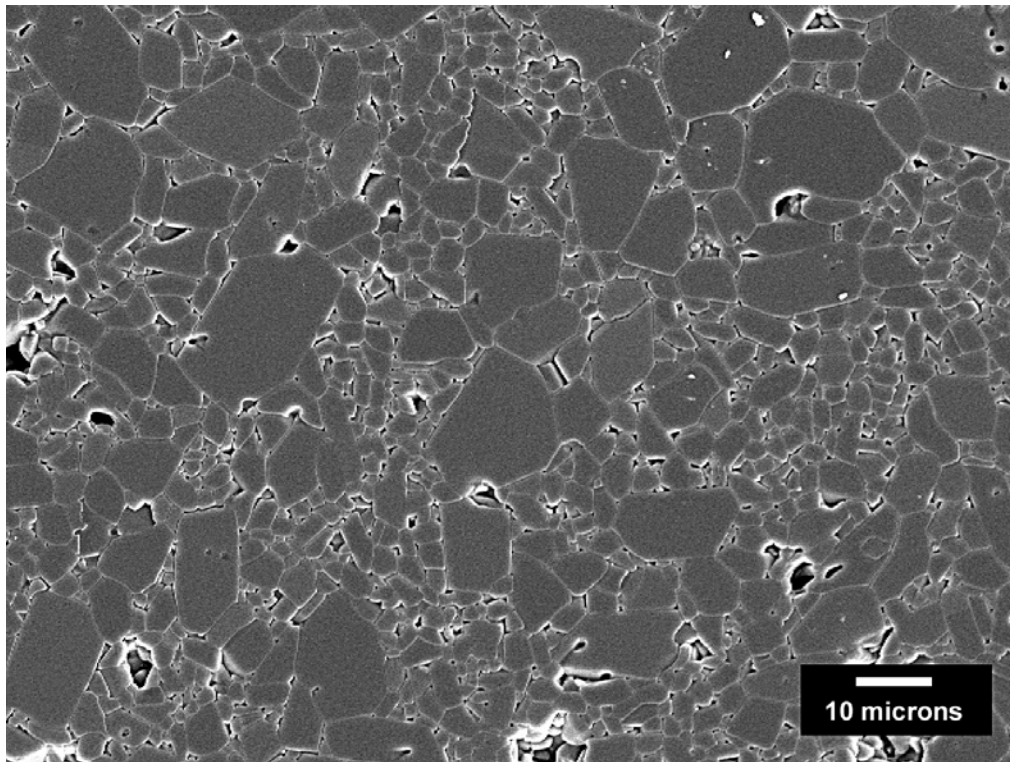


Figure 1. Microstructure of the CoorsTek AD-995 alumina (ALOX) after thermal etching.

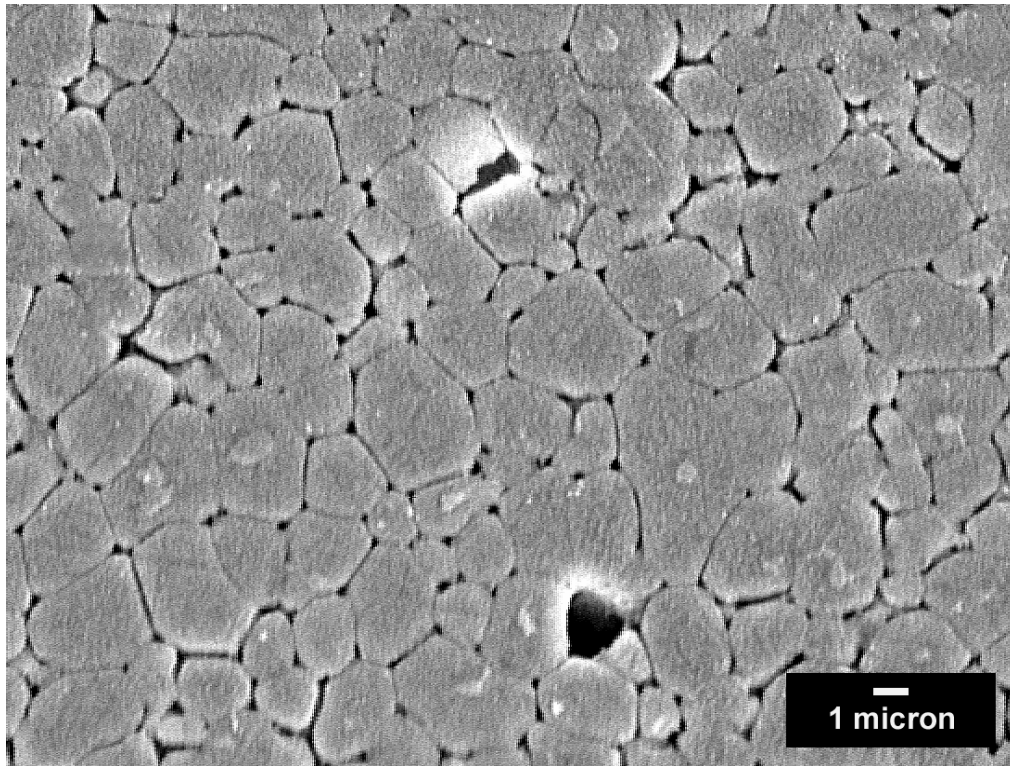


Figure 2. Microstructure of the CoorsTek Ce-TZP zirconia (ZrO<sub>2</sub>) after thermal etching.

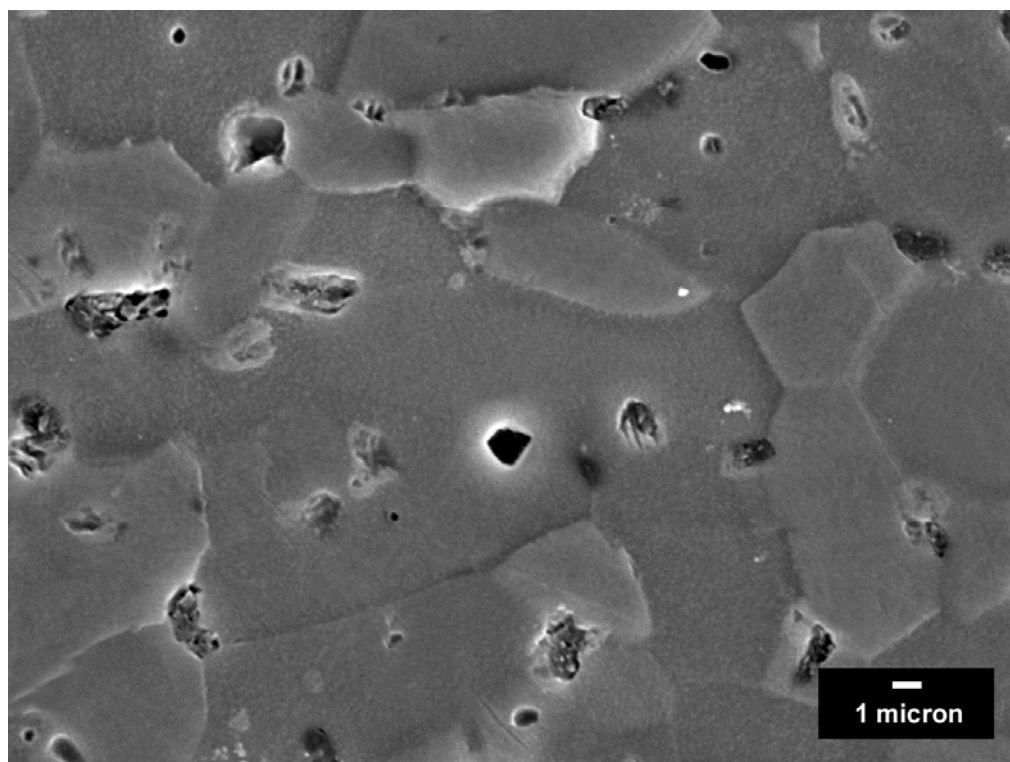


Figure 3. Microstructure of the Saint-Gobain enhanced hexoloy SA silicon carbide (SCEH).

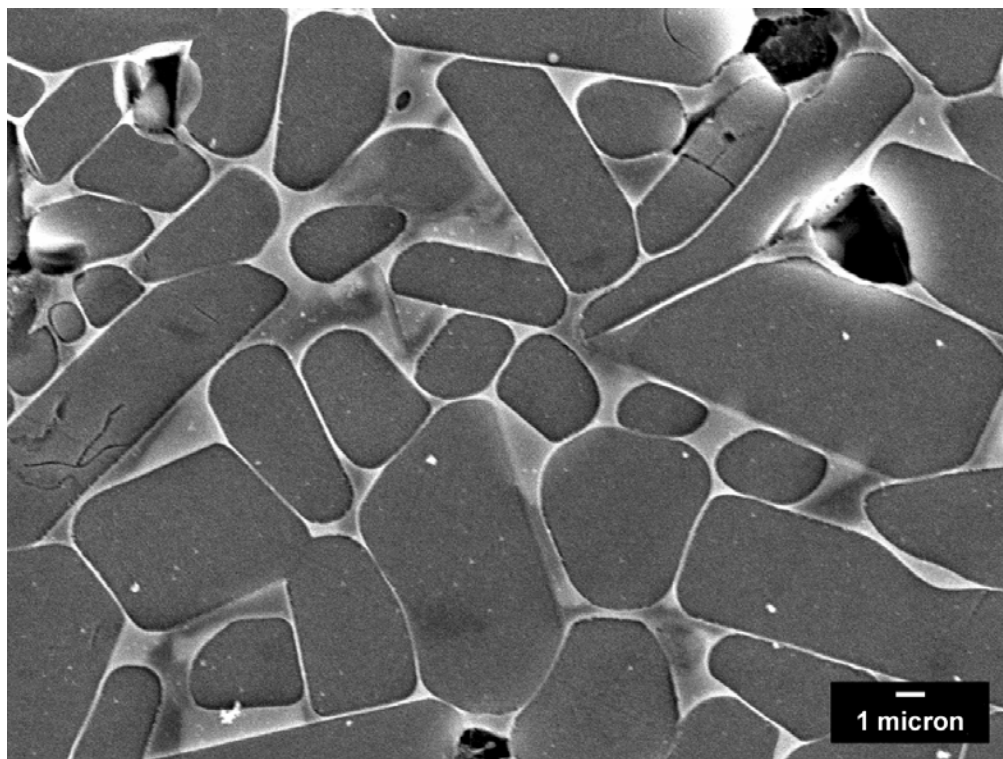


Figure 4. Microstructure of the Saint-Gobain liquid phase sintered hexoloy SA silicon carbide (SCLH).

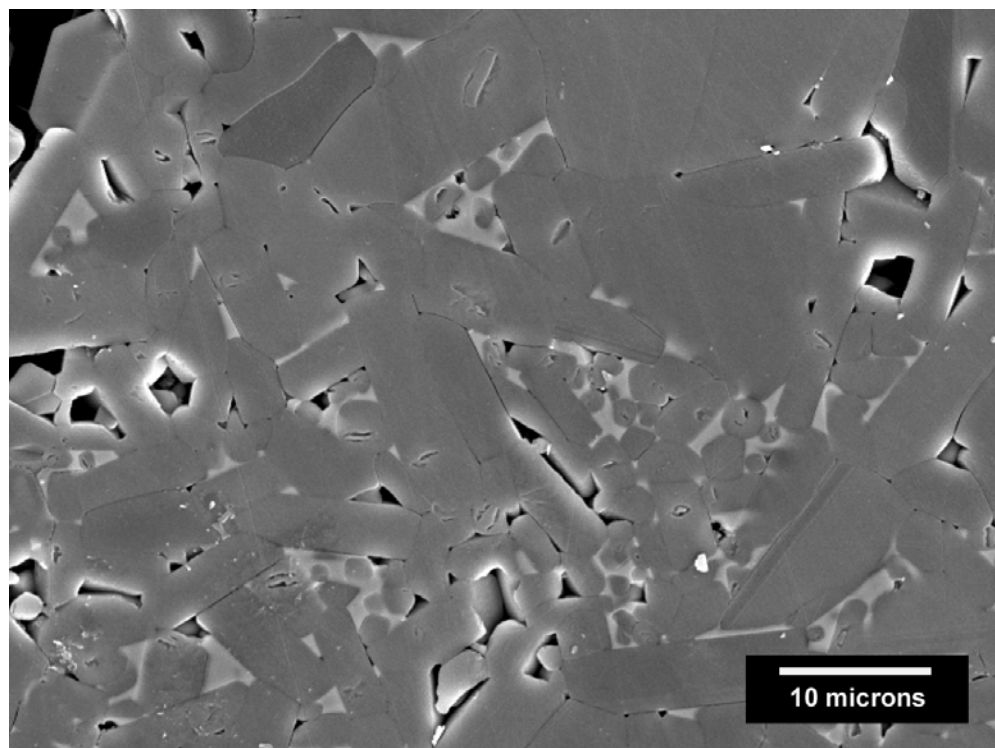


Figure 5. Microstructure of the ceradyne ceralloy 146-5S silicon carbide (SC46).



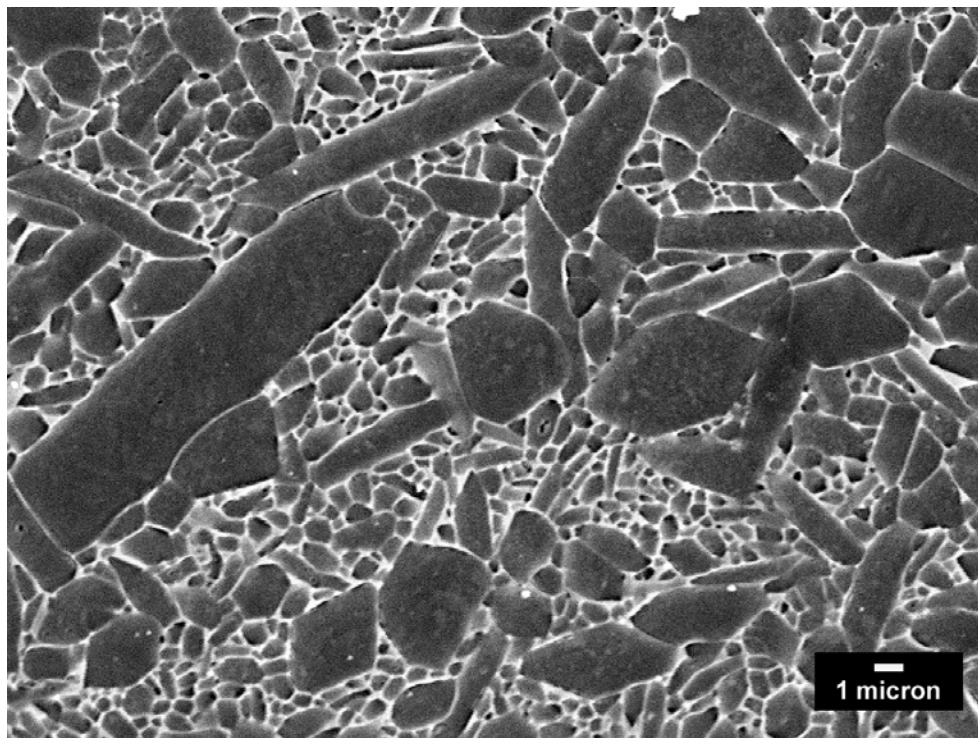


Figure 6. Microstructure of the ceradyne ceralloy 147-31N silicon nitride (SN47) after etching in molten KOH.

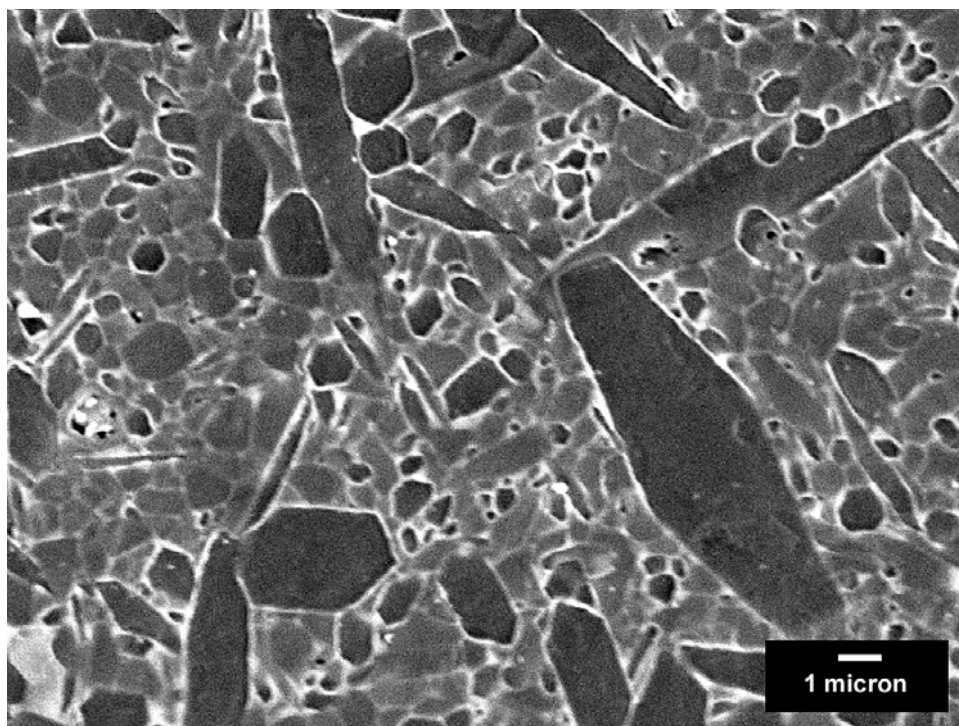


Figure 7. Microstructure of the Kennametal TK4 SiAlON (STK4) after etching in molten KOH.

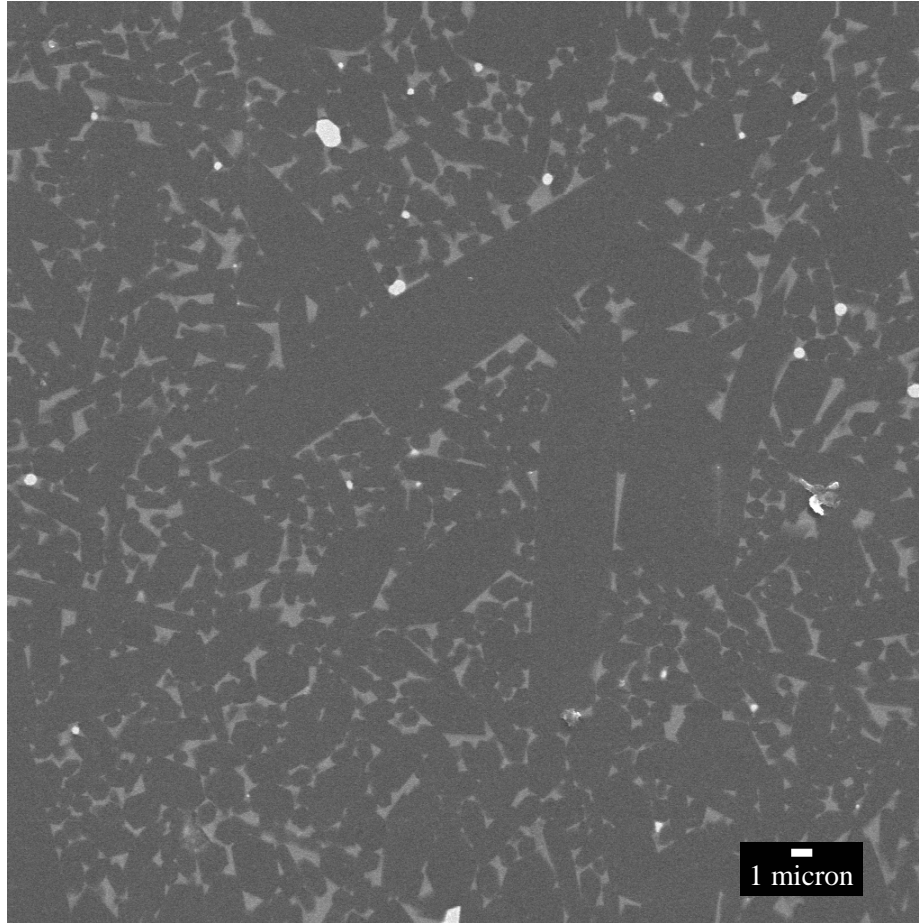


Figure 8. Microstructure of the Kyocera SN235P (SN5P) after plasma etching.

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### 3. Experimental Procedure

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All of the specimens required to generate the mechanical and thermal property data in this report were prepared using conventional diamond grinding methods.

#### 3.1 Elastic Properties

Modal analysis resulting from finite-element analysis (FEA) (e.g., ANSYS), in combination with the capturing of resonance frequencies using resonant ultrasound spectroscopy (RUS) from any two of the three resonance modes (i.e., flexural, torsional, and longitudinal), was used in the determination of the elastic properties of the eight candidate ceramics. The method consisted of (1) running three FEA modal analyses for a given geometry and material density to “bracket” two of the three elastic constants (e.g.,  $E$  and  $\nu$ ), and (2) fitting their functionalities to the measured resonance frequencies. For example, if the ceramic was a  $\text{Si}_3\text{N}_4$ , and its  $E$  and  $\nu$  were estimated to be 300 GPa and 0.25, respectively, then the three  $E$ - $\nu$  combinations for the three

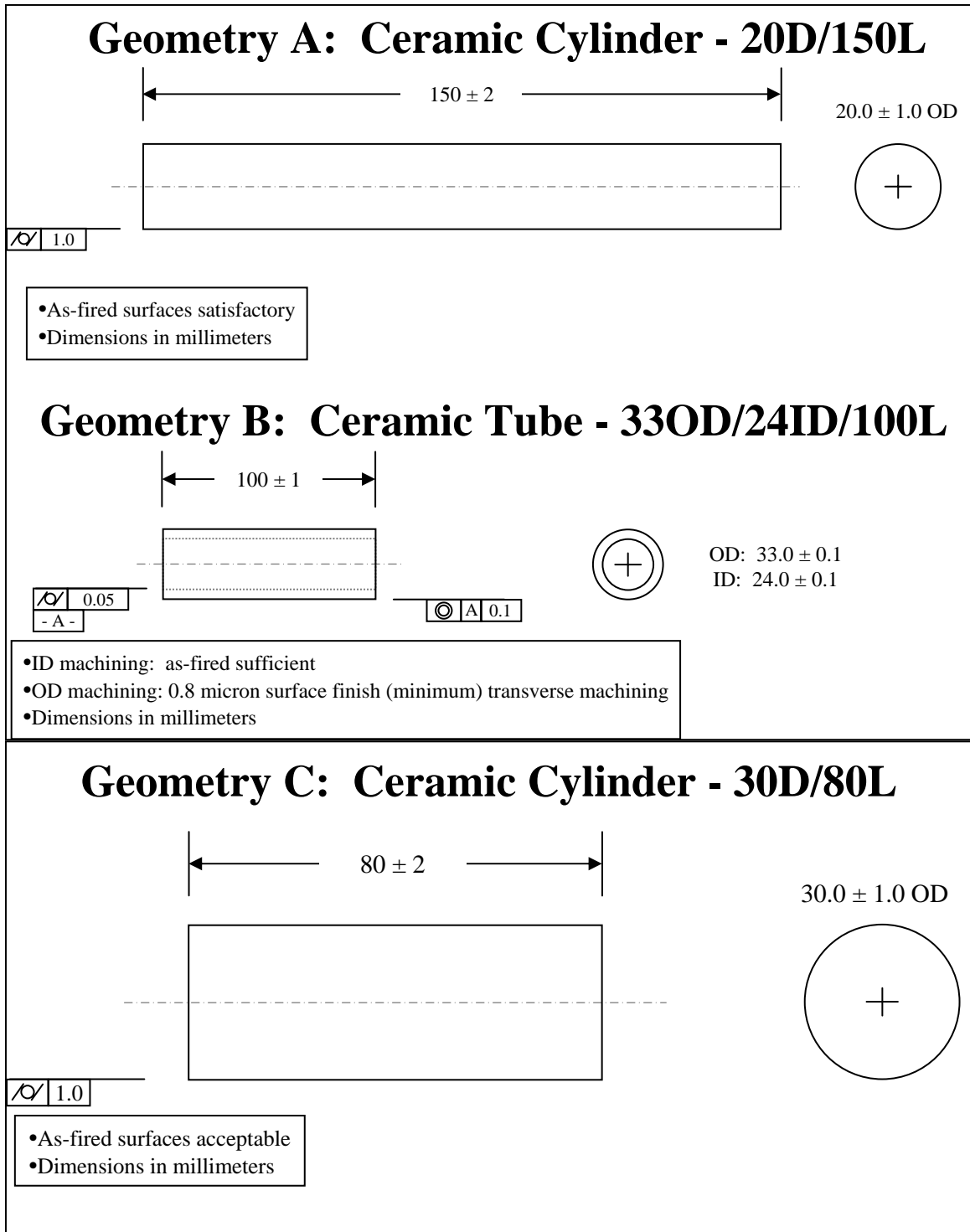


Figure 9. Material geometries ordered from each manufacturer.

modal analyses could be (semi-arbitrarily) chosen to be 150 GPa - 0.15, 450 GPa - 0.15, and 450 GPa - 0.30. These FEA results then enabled the determination of the torsional frequency ( $f_{\text{tors}}$ ) and a flexural resonant frequency ( $f_{\text{flex}}$ ) as multilinear functions of  $E$  and  $\nu$  for the modeled geometry and density; namely,

$$f_{\text{tors}} = A_t + B_t \bullet E + C_t \bullet \nu \quad (1)$$

and

$$f_{\text{flex}} = A_f + B_f \bullet E + C_f \bullet \nu, \quad (2)$$

where  $A_t$ ,  $B_t$ , and  $C_t$  are regression constants for  $f_{\text{tors}}$  and  $A_f$ ,  $B_f$ , and  $C_f$  are constants for  $f_{\text{flex}}$ .

A torsional ( $f_{\text{tors}}$ ) and flexural ( $f_{\text{flex}}$ ) resonance frequency were measured with the RUS and then applied against equations 1 and 2. There is not a unique combination of  $E$  and  $\nu$  that singly represents the measured torsional or flexural frequency but instead a locus of  $E$ - $\nu$  pairs that do; however, a unique  $E$ - $\nu$  combination does result when those two resonances are combined.

### 3.2 Mechanical Properties

Three different specimens were prepared and used to determine the strength of each ceramic. Uniaxial tension tests were used in an attempt to promote the volume-distributed flaws in the material while c-ring and sector flexure tests highlighted the surface-distributed machining flaws. The c-ring testing specifically addressed the machining flaws introduced perpendicular to the circumferential grinding done on the outer diameter of the tubes, while the sector flexure tests highlighted the parallel machining flaws associated with this grinding direction.

Cylindrical button-head tensile specimens were machined from the geometry A components (figure 9) to the gage section dimensions listed in figure 9 of ASTM C1273 (1), with an overall specimen length of 135 mm. The room temperature uniaxial strength was determined using 15–20 specimens per material following the guidelines and equations in ASTM C1273. The uniaxial tensile strength was calculated using this equation:

$$S_u = \frac{P_{\text{max}}}{A}, \quad (3)$$

where  $S_u$  is the tensile strength,  $P_{\text{max}}$  is the breaking load, and  $A$  is the cross-sectional area of the specimen.

C-ring specimens having a width of 8 mm with longitudinal 45° chamfers to a distance of 0.15 mm, and a slot height of 5.7 mm were machined from the tubular components

(geometry B) and tested in accordance with ASTM C1323 (2). A displacement rate of 0.5 mm/min was used to compressively and diametrically load 16 to 18 c-ring specimens to failure for each material. Paper shims were placed between the upper and lower contact locations to minimize the likelihood of contact-induced fracture. The geometry and failure loads were used to calculate the hoop or OD tangential failure stress ( $\sigma_{\theta\max}$ ) for each specimen according to the strength of materials solution in ASTM C1323:

$$\sigma_{\theta\max} = \frac{PR}{btr_o} \left[ \frac{r_o - r_a}{r_a - R} \right], \quad (4)$$

where P is the failure load,  $R = (r_o - r_i)/\ln(r_o/r_i)$ ,  $r_o$  is the outer c-ring radius,  $r_i$  is the inner c-ring radius,  $r_a$  is the average of  $r_o$  and  $r_i$ , b is width, and t is thickness or  $r_o - r_i$ .

A new test specimen configuration, the sectoried tube flexure specimen, was also machined from the tubular component according to the guidelines shown in figure 10. These specimens were then broken in four-point flexure at room temperature using inner and outer spans of 40 mm and 80 mm, respectively, with a loading rate of 1 mm/min. The upper and lower supports were made of SiC with the lower support contoured to fit the outer radius of the specimen to achieve line loading (figure 11).

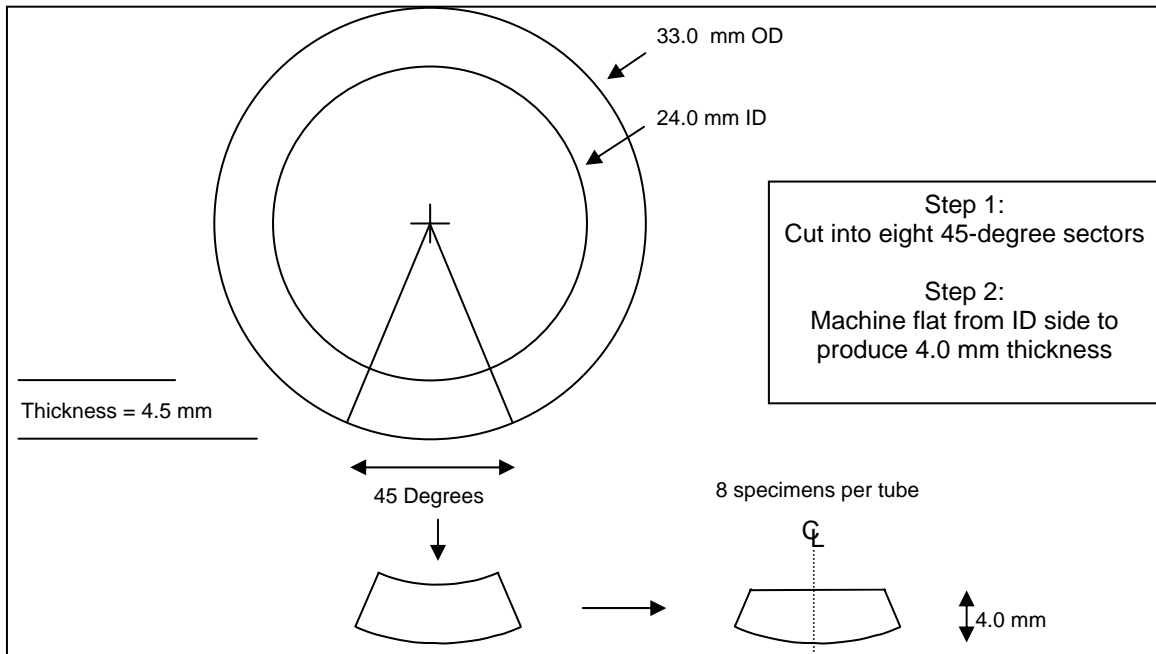


Figure 10. Schematic for the fabrication of sectoried tube flexure specimens.

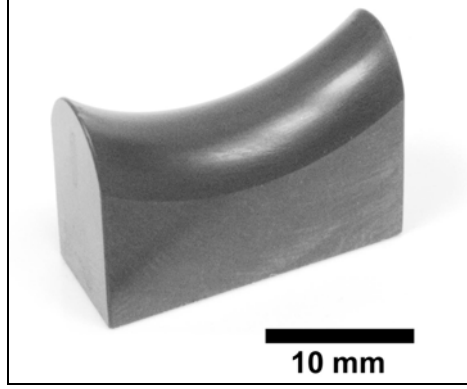


Figure 11. SiC lower support used in the room and elevated temperature sector flexure testing.

The sector flexure strength was also determined at 700 °C using the same loading configuration and loading rate, and with a heating rate of 10 °C/min. The specimen was held at temperature for 10 min before the load was applied. Twenty specimens were used to determine the room temperature strength and 10 were used to determine the elevated temperature strength. The sector flexure strength ( $\sigma_{flex}$ ) was calculated using

$$\sigma_{flex} = \frac{P(L_2 - L_1)c}{4I}, \quad (5)$$

where  $P$  is the failure load,  $L_1$  is the upper span,  $L_2$  is lower span,  $c$  is the distance between the neutral axis and the outer fiber, and  $I$  is moment of inertia. The moment of the inertia,  $I$ , in equation 5 can be determined through correct usage of the parallel axis theorem in combination with equations 6–11.

$$I = I_{zz-Sect} - I_{zz-Tri}, \quad (6)$$

where  $I_{zz-Sect}$  is the moment of inertia of a sector of a solid cylinder and  $I_{zz-Tri}$  is the moment of inertia of a triangle whose subtraction from the sectored solid cylinder will produce a specimen with the cross section shown in figure 10. Generically, the moment of inertia of the sectored solid cylinder is

$$I_{zz-Sect} = I_A + \alpha R_o^2 \left[ R_o \left( 1 - \frac{2 \sin \alpha}{3\alpha} \right) - \bar{Y} \right]^2, \quad (7)$$

where  $\alpha = 22.5^\circ$  (and hence  $2\alpha = 45^\circ$ ),  $R_o$  is the outer radius (16.5 mm), and

$$I_A = \frac{1}{4} R_o^4 \left[ \alpha + \frac{1}{2} \sin(2\alpha) \right] - \frac{4}{9\alpha} R_o^4 \sin^2 \alpha, \quad (8)$$

and the centroid for the sectored flexure specimen is

$$\bar{Y} = \frac{\alpha R_o^3 \left[ 1 - \frac{2 \sin \alpha}{3\alpha} \right] - \left( \frac{R_o + 2h}{3} \right) (R_o - h)^2 \tan \alpha}{\alpha R_o^2 - (R_o - h)^2 \tan \alpha}, \quad (9)$$

where  $h$  is the specimen height (4 mm). The value of the parameter  $c$  in equation 5 is simply  $R_o - Y$ . The moment of inertia of the triangle in equation 6 is

$$I_{zz-Tri} = I_B + (R_o - h)^2 \tan \alpha \left[ \frac{R_o + 2h}{3} - \bar{Y} \right]^2, \quad (10)$$

where

$$I_B = \frac{(R_o - h)^4}{18} \tan \alpha. \quad (11)$$

Each set of raw strength data was subsequently analyzed using a two-parameter Weibull regression according to ASTM C1239 (3). This analysis yielded a biased Wiebull modulus and characteristic strength.

Fracture toughness was determined using the procedures and equations in ASTM C1421 (4). Chevron notch specimens, nominally  $3 \times 4 \times 50$  mm in size with the D configuration notch ( $a_0 = 1.40 \pm 0.07$  mm), were machined and then fractured in three- or four-point bending. The fracture toughness ( $K_{Ivb}$ ) was calculated using

$$K_{Ivb} = Y_{\min}^* \left[ \frac{P_{\max} (S_o - S_i) 10^{-6}}{bw^{3/2}} \right], \quad (12)$$

where  $Y_{\min}^*$  is the minimum stress intensity factor,  $P_{\max}$  is the relevant maximum load that occurs during stable crack propagation,  $S_o$  and  $S_i$  are outer and inner support spans, respectively,  $b$  is the specimen width, and  $w$  the specimen height.

The Vickers hardness ( $H_v$ ) was determined for each material from room temperature to 800 °C and in select materials to 1000 °C using an indentation load of 300 g on a Nikon QM2 hardness machine.

### 3.3 Thermal Properties

The thermal conductivity, heat capacity, and coefficient of thermal expansion (CTE) were determined for all eight materials between room temperature and 1000 °C. ASTM E1461 (5) and ASTM C714 (6) were used to obtain thermal diffusivity and heat capacity values using the laser flash method on specimens nominally  $8 \times 8 \times 2$  mm in size. A thermal conductivity was calculated from these values. The linear coefficient of thermal expansion was obtained using a prismatic specimen nominally  $3 \times 4 \times 25$  mm in size. Tests were conducted in a dual-rod dilatometer using a heating rate of 1 °C/min following

the procedure outlined in ASTM E228 (7). The data collection rate for this test was 2 datapoints/°C.

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## 4. Elastic Property Results

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The results for room temperature E and  $\nu$  for specimens that had nominal dimensions of  $2 \times 8 \times 8$  mm, as well as the calculated shear modulus (G), are summarized in table 2.

Table 2. Room temperature elastic properties measured as determined by resonant ultrasound spectroscopy (RUS).

| Material | Density<br>(g/cm <sup>3</sup> ) | E<br>(GPa) | Poisson's Ratio<br>( $\nu$ ) | G<br>(GPa) |
|----------|---------------------------------|------------|------------------------------|------------|
| ALOX     | 3.875                           | 384        | 0.226                        | 157        |
| ZRO2     | 6.022                           | 195        | 0.249                        | 78         |
| SCEH     | 3.135                           | 425        | 0.161                        | 193        |
| SCLH     | 3.152                           | 387        | 0.173                        | 165        |
| SC46     | 3.104                           | 405        | 0.167                        | 174        |
| SN47     | 3.183                           | 326        | 0.258                        | 130        |
| STK4     | 3.349                           | 336        | 0.247                        | 135        |
| SN5P     | 3.193                           | 313        | 0.253                        | 125        |

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## 5. Mechanical Property Results

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The mechanical properties for each candidate gun barrel ceramic are summarized in table 3; the raw data can be found in appendix A. The average strength values listed in this table are graphically depicted in figure 12 and the uncensored Weibull modulus information is shown in figure 13. The two Si<sub>3</sub>N<sub>4</sub> materials and the SiAlON are the strongest group of materials, but the Weibull modulus data shows that, even though these materials possess high average strength values, there is a relatively wide distribution in strength. Fractography and data censoring of each material is underway. These results along with the censored strength data will be the subject of a separate report.

The hardness of each ceramic was essentially linear between room temperature and 800–1000 °C, but the hardness decreases at a different rate for each ceramic. Figure 14 graphically depicts the hardness of all eight ceramics, while figures 15–17 show with better clarity the linear decrease in hardness for each class of ceramic. The SCEH has the highest hardness value at room temperature, but this value drops significantly as the temperature increases. The hardest materials at room temperature after the SCEH are the SCLH, SC46, and STK4 ceramics, which all have hardness values around 20 GPa. However, only three materials (SCEH, SN47, and STK4) have hardness values above



Table 3. Summary of mechanical properties for candidate gun barrel ceramics.

| Property                                    | Manufacturer    |                 |                 |                 |                 |                 |                 |                 |
|---|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|   | ALOX            | ZRO2            | SCEH            | SCLH            | SC46            | SN47            | STK4            | SN5P            |
| Avg. Tensile Strength (MPa)                 | 314             | 558             | 320             | 286             | 284             | 784             | 446             | 586             |
| Weibull Modulus                             | 17.1            | 22.2            | 10.0            | 14.7            | 21.5            | 9.4             | 9.3             | 16.9            |
| Avg. Sect Flex Strength (MPa)               |                 |                 |                 |                 |                 |                 |                 |                 |
| 25 °C                                       | 265             | 578             | 192             | 311             | 271             | 546             | 653             | 563             |
| 700 °C                                      | 241             | 119             | 243             | 301             | 284             | 618             | 691             | 528             |
| Weibull Modulus                             |                 |                 |                 |                 |                 |                 |                 |                 |
| 25 °C                                       | 31.5            | 22.9            | 5.5             | 12.9            | 29.3            | 12.0            | 12.7            | 10.8            |
| 700 °C                                      | 20.4            | 9.1             | 4.9             | 12.6            | 21.0            | 17.2            | 23.9            | 15.7            |
| Avg. C-ring Strength (MPa)                  | 275             | 581             | 299             | 330             | 276             | 753             | 694             | 654             |
| Weibull Modulus                             | 17.4            | 9.3             | 4.6             | 9.5             | 14.4            | 13.7            | 4.7             | 12.3            |
| $K_{Ic}$ (MPa* $\sqrt{m}$ ) (Chevron Notch) | $3.94 \pm 0.12$ | $5.68 \pm 0.36$ | $3.02 \pm 0.06$ | $2.42 \pm 0.09$ | $4.99 \pm 0.15$ | $6.58 \pm 0.14$ | $7.61 \pm 0.11$ | $8.67 \pm 0.19$ |
| Hardness (Hv) – 300g (GPa)                  |                 |                 |                 |                 |                 |                 |                 |                 |
| 25 °C                                       | $15.9 \pm 1.2$  | $8.6 \pm 1.6$   | $27.1 \pm 0.3$  | $20.8 \pm 0.4$  | $20.7 \pm 2.9$  | $14.7 \pm 0.1$  | $19.9 \pm 0.5$  | $13.6 \pm 0.4$  |
| 200 °C                                      | $13.1 \pm 1.2$  | $8.0 \pm 0.5$   | $24.8 \pm 0.6$  | $16.6 \pm 0.2$  | $17.9 \pm 1.1$  | $13.3 \pm 0.1$  | $17.9 \pm 0.5$  | $12.4 \pm 0.6$  |
| 300 °C                                      | $13.1 \pm 0.7$  | $7.1 \pm 0.2$   | —               | —               | $18.3 \pm 1.2$  | —               | —               | —               |
| 400 °C                                      | $10.7 \pm 0.8$  | $5.5 \pm 0.1$   | $19.1 \pm 0.3$  | $14.0 \pm 0.4$  | $16.9 \pm 1.2$  | $12.5 \pm 0.2$  | $15.9 \pm 0.4$  | $11.6 \pm 0.4$  |
| 500 °C                                      | $9.7 \pm 0.9$   | $4.6 \pm 0.2$   | —               | —               | $15.0 \pm 1.3$  | —               | —               | —               |
| 600 °C                                      | $8.0 \pm 1.3$   | $3.9 \pm 0.3$   | $15.5 \pm 0.3$  | $12.0 \pm 0.3$  | $12.3 \pm 1.3$  | $11.4 \pm 0.3$  | $14.8 \pm 0.5$  | $10.0 \pm 0.3$  |
| 700 °C                                      | $7.1 \pm 0.2$   | $3.6 \pm 0.1$   | —               | —               | $10.7 \pm 1.9$  | —               | —               | —               |
| 800 °C                                      | $4.8 \pm 0.9$   | $3.0 \pm 0.3$   | $11.4 \pm 0.3$  | $9.8 \pm 0.3$   | $9.8 \pm 0.4$   | $10.7 \pm 0.3$  | $13.7 \pm 0.2$  | $9.0 \pm 0.5$   |

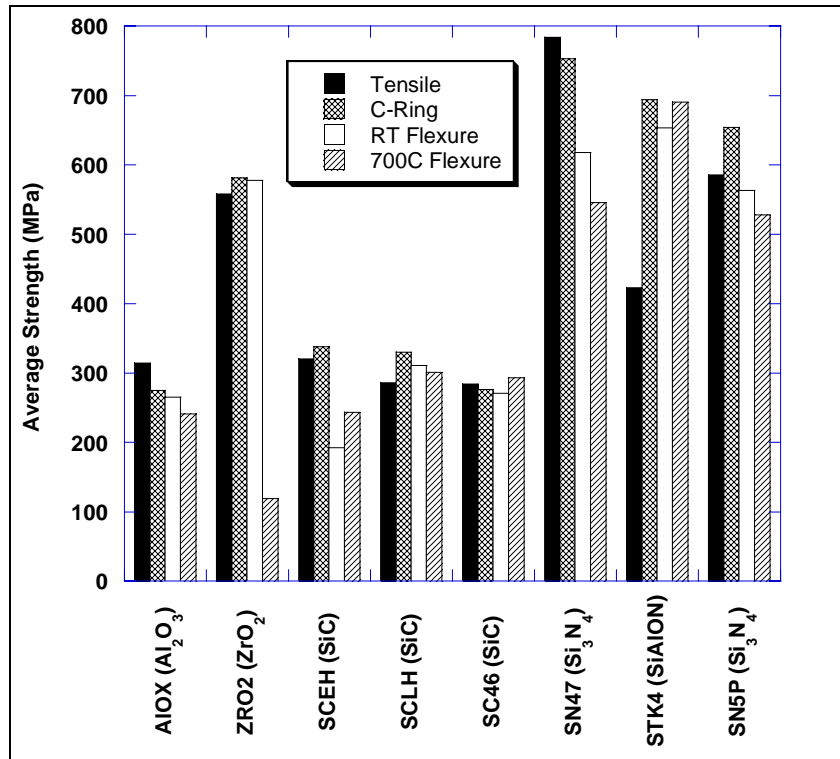


Figure 12. Uncensored average strength data.

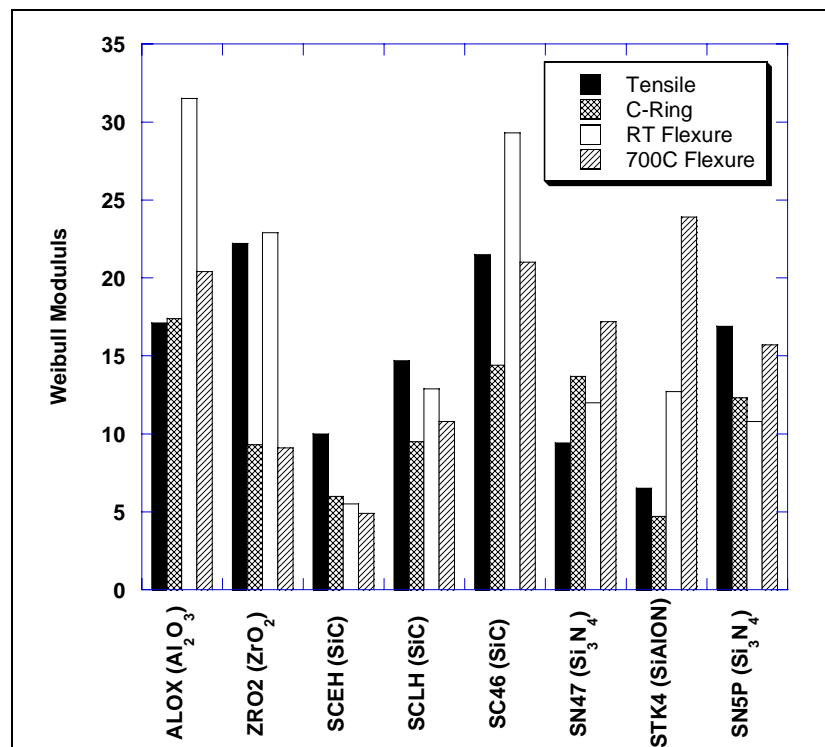


Figure 13. Uncensored Weibull modulus.

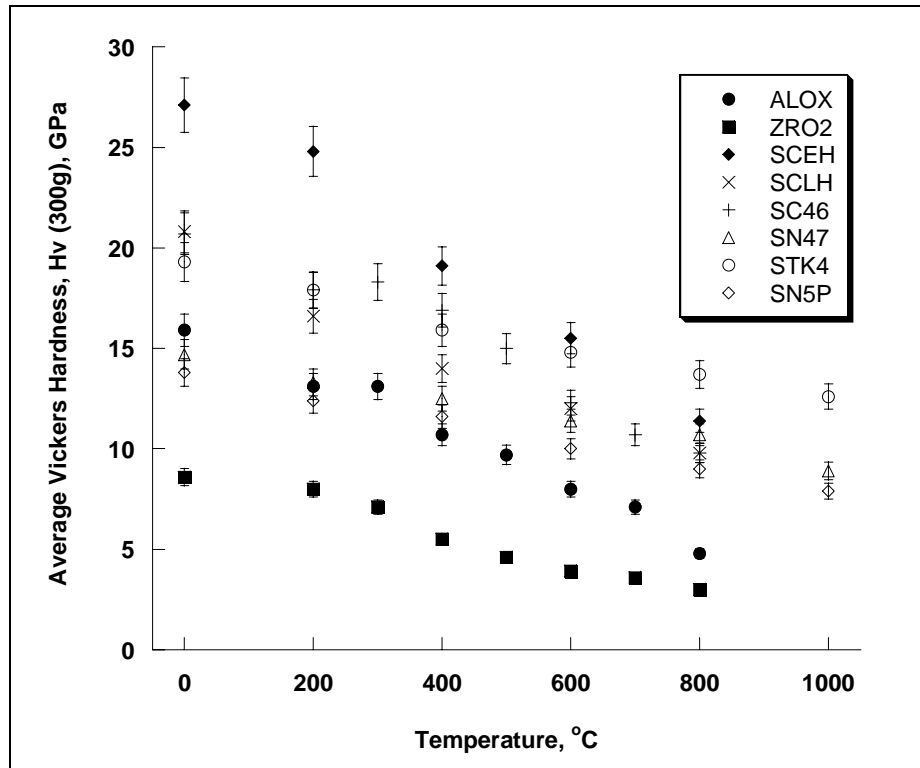


Figure 14. Hardness as a function of temperature for all eight ceramics.

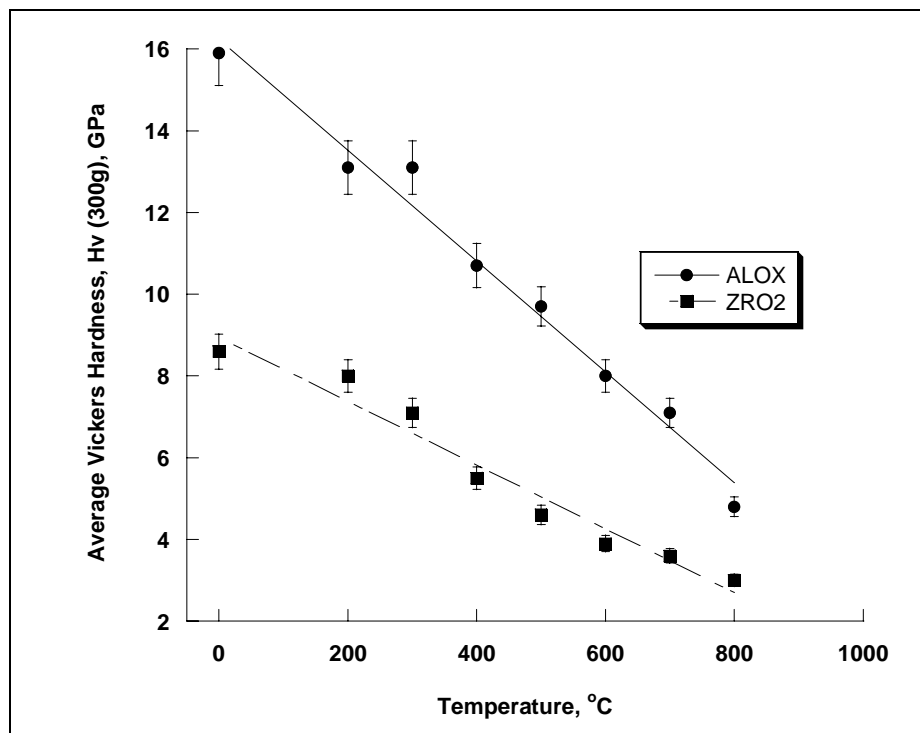


Figure 15. Hardness as a function of temperature for ALOX and ZRO2.

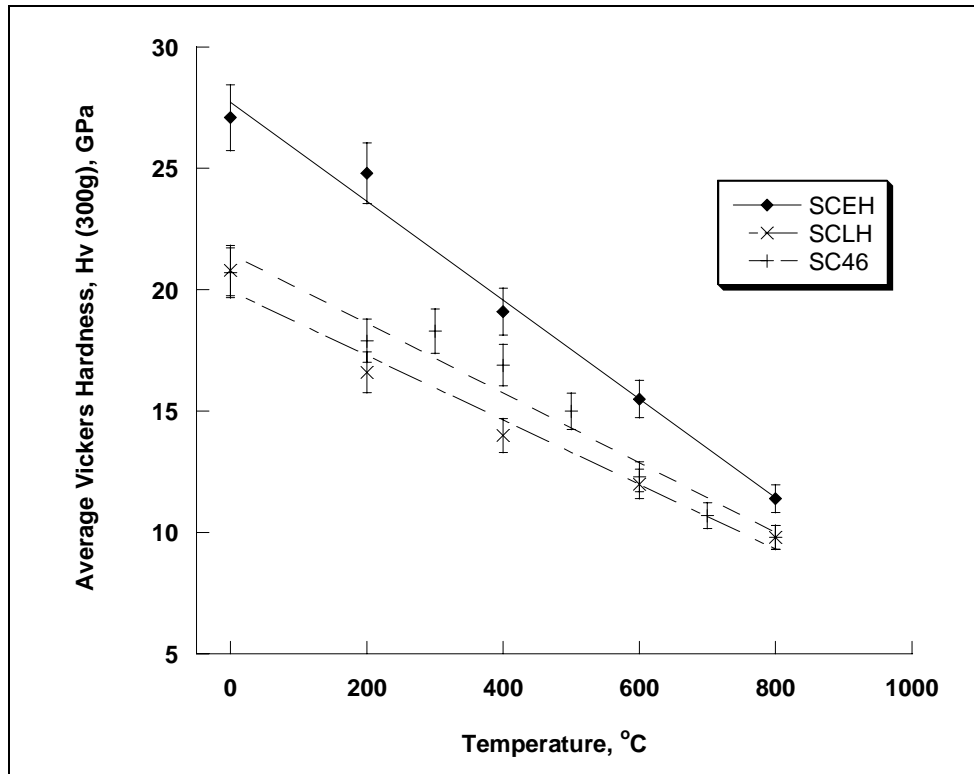


Figure 16. Hardness as a function of temperature for the SiC ceramics.

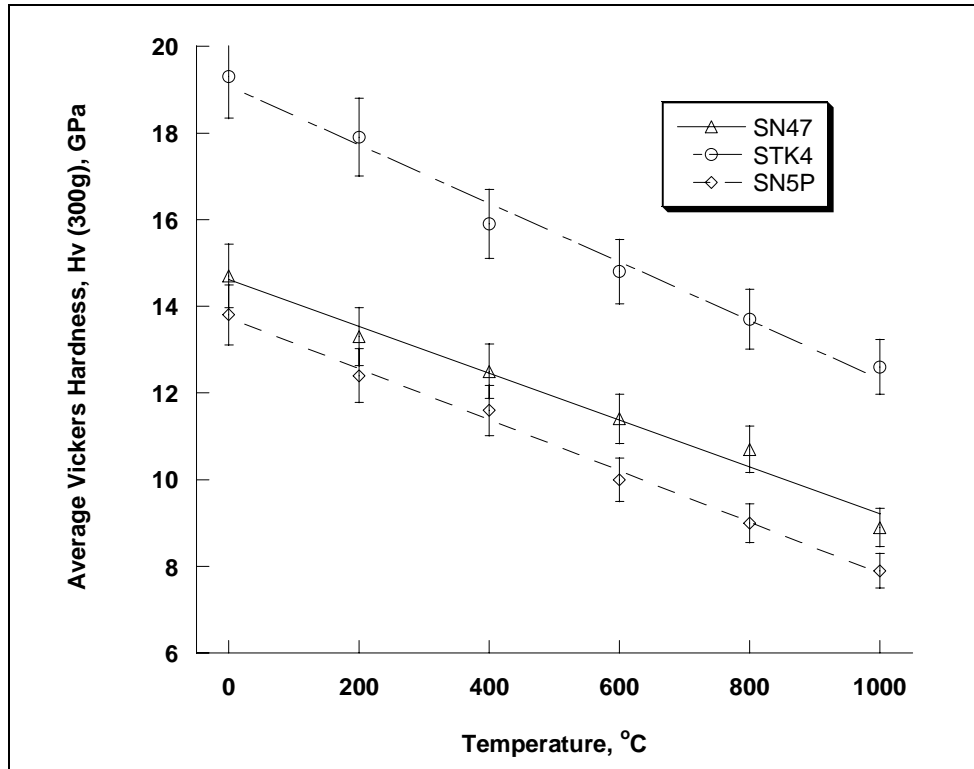


Figure 17. Hardness as a function of temperature for the Si<sub>3</sub>N<sub>4</sub> ceramics.

10 GPa at 800 °C. The hot hardness of the SN47 and STK4 ceramics was measured at two different times with a different indenter but by the same operator using the same hardness machine. The first set of data was measured from room temperature to 800 °C and the second set from room temperature to 1000 °C. Only the second set of data is included in the table and figure. All the data is, however, included in the appendix. There was no significant difference in the hardness values for these two ceramics measured at different times.

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## 6. Thermal Property Results

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The average thermal conductivity, heat capacity, and CTE for each candidate gun barrel ceramic are summarized in table 4, and the raw data for these three thermal properties can be found in appendix B. As expected, the thermal conductivity of the three SiC ceramics was the highest, and the ZRO2 was the lowest, while the ALOX, both silicon nitrides, and the SiAION had values well below the SiCs, but not as low as the ZRO2. The heat capacity of all the ceramics was very similar except the ZRO2, which was significantly lower. The oxides have the largest average CTE, followed by the SiCs, and then the nitrides.

Table 4. Summary of the average thermal properties of the candidate gun barrel ceramics between room temperature and 1000 °C.

| Material    | Property                 |                               |   |
|-------------|--------------------------|-------------------------------|---|
|             | TC, $\lambda$<br>(W/m-K) | Heat Capacity, Cp<br>(J/kg-K) | Avg. CTE<br>( $\times 10^{-6}/^{\circ}\text{C}$ ) |
| <b>ALOX</b> | 31.4–7.2                 | 788–1300                      | 8.5   |
| <b>ZRO2</b> | 3.13–2.21                | 462–640                       | 11.8  |
| <b>SCEH</b> | 170–45.2                 | 719–1250                      | 4.5   |
| <b>SCLH</b> | 74.6–33.2                | 733–1270                      | 4.9   |
| <b>SC46</b> | 99.9–37.3                | 696–1280                      | 4.9   |
| <b>SN47</b> | 26.5–14.1                | 690–1270                      | 3.2   |
| <b>STK4</b> | 10.8–8.49                | 736–1240                      | 3.3   |
| <b>SN5P</b> | 32.2–16.1                | 695–1250                      | 3.4   |

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## 7. Summary

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A mechanical and thermal property database was created for eight commercially-available ceramics under consideration for gun barrel applications. The mechanical properties measured included strength, fracture toughness, and Vickers hardness. An uncensored Weibull analysis was performed on all of the strength data that was generated. Thermal conductivity, specific heat, and linear CTE were also determined between room temperature and 1000 °C for each material. All of this data was incorporated in a probabilistic modeling effort to predict ceramic performance, identify an optimum ceramic gun barrel design for various caliber systems, and rank and down select ceramics for further evaluation. The modeling and design aspects of this ceramic gun barrel effort will be detailed in subsequent reports.

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## 8. References

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1. ASTM C1273. Standard Test Method for Tensile Strength of Monolithic Advanced Ceramics at Ambient Temperatures. *Annu. Book ASTM Stand.* **2003**, Vol. 15.01.
2. ASTM C1323. Standard Test Method for Ultimate Strength of Advanced Ceramics with Diametrically Compressed C-Ring Specimens at Ambient Temperatures. *Annu. Book ASTM Stand.* **2003**, Vol. 15.01.
3. ASTM C1239. Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters fro Advanced Ceramics. *Annu. Book ASTM Stand.* **2003**, Vol. 15.01.
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## **Appendix A. Mechanical Properties**

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## A-1. Room Temperature Strength Data From C-Ring Specimens

Table A-1.1. C-ring data for CoorsTek AD995 (ALOX).

| Specimen                | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | $\theta$<br>(°) |
|-------------------------|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|-----------------|
| ALOX-B1-1               | 33.03      | 23.88      | 5.69         | 8.04              | 4.58             | 11.89       | 3.858                           | 631.8       | 271.8           | 32.85            | 2.05            |
| ALOX-B1-2               | 33.04      | 23.89      | 5.69         | 8.05              | 4.58             | 11.90       | 3.855                           | 542.8       | 233.3           | 32.94            | 1.00            |
| ALOX-B1-3               | 33.03      | 23.75      | 5.68         | 8.04              | 4.64             | 11.92       | 3.822                           | 644.9       | 268.4           | 32.20            | 15.84           |
| ALOX-B1-4               | 33.02      | 23.84      | 5.70         | 8.04              | 4.59             | 11.93       | 3.862                           | 593.8       | 253.4           | 32.62            | 7.91            |
| ALOX-B1-5               | 33.02      | 23.94      | 5.69         | 8.04              | 4.54             | 11.91       | 3.891                           | 693.1       | 303.5           | 32.14            | 16.59           |
| ALOX-B1-6               | 33.04      | 23.91      | 5.69         | 8.03              | 4.57             | 11.91       | 3.875                           | 659.2       | 285.5           | 32.90            | 0.64            |
| ALOX-B1-7               | 33.03      | 23.75      | 5.64         | 8.03              | 4.64             | 11.90       | 3.819                           | 673.4       | 280.6           | 32.65            | 7.57            |
| ALOX-B1-8               | 33.03      | 23.86      | 5.75         | 8.05              | 4.59             | 11.91       | 3.855                           | 653.2       | 279.2           | 32.61            | 8.27            |
| ALOX-B1-9               | 33.03      | 23.72      | 5.75         | 8.04              | 4.66             | 11.91       | 3.812                           | 664.1       | 274.2           | 32.93            | 1.11            |
| ALOX-B2-1               | 33.03      | 23.79      | 5.66         | 8.03              | 4.62             | 11.85       | 3.817                           | 668.2       | 281.3           | 32.91            | 0.10            |
| ALOX-B2-2               | 33.02      | 23.82      | 5.69         | 8.05              | 4.60             | 11.88       | 3.834                           | 654.3       | 277.4           | 32.85            | 1.71            |
| ALOX-B2-3               | 33.02      | 23.94      | 5.64         | 8.05              | 4.54             | 11.86       | 3.867                           | 661.2       | 289.2           | 32.68            | 6.62            |
| ALOX-B2-4               | 33.03      | 23.90      | 5.74         | 8.05              | 4.57             | 11.86       | 3.853                           | 662.4       | 286.1           | 32.70            | 6.20            |
| ALOX-B2-5               | 33.02      | 23.89      | 5.72         | 8.04              | 4.57             | 11.88       | 3.865                           | 683.7       | 295.5           | 32.25            | 14.82           |
| ALOX-B2-6               | 33.04      | 23.91      | 5.69         | 8.04              | 4.57             | 11.85       | 3.851                           | 652.0       | 282.1           | 32.81            | 3.61            |
| ALOX-B2-7               | 33.02      | 23.78      | 5.74         | 8.03              | 4.62             | 11.88       | 3.832                           | 678.4       | 285.4           | 32.96            | 3.10            |
| ALOX-B2-8               | 33.01      | 23.78      | 5.70         | 8.02              | 4.62             | 11.88       | 3.840                           | 648.9       | 273.9           | 32.36            | 12.83           |
| ALOX-B2-9               | 33.01      | 23.88      | 5.70         | 8.04              | 4.57             | 11.86       | 3.859                           | 582.8       | 251.8           | 31.72            | 22.20           |
| m = 17.35               |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| sigma_theta = 282.3 MPa |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| sigma_avg = 275.3 MPa   |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| std dev = 16.6 MPa      |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |

Table A-1.2. C-ring data for CoorsTek Ce-TZP (ZRO2).

| Specimen                | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | $\theta$<br>(°) |
|-------------------------|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|-----------------|
| ZRO2-B1-1               | 33.05      | 23.85      | 5.85         | 8.03              | 4.60             | 18.87       | 6.110                           | 1423.5      | 605.8           | 32.81            | 3.62            |
| ZRO2-B1-2               | 33.07      | 23.92      | 5.81         | 8.01              | 4.58             | 18.77       | 6.112                           | 1486.2      | 642.8           | 32.95            | 0.35            |
| ZRO2-B1-3               | 33.05      | 23.81      | 5.88         | 8.06              | 4.62             | 18.86       | 6.064                           | 1306.9      | 548.5           | 32.68            | 6.91            |
| ZRO2-B1-4               | 33.04      | 23.83      | 5.80         | 8.03              | 4.61             | 18.81       | 6.083                           | 1423.4      | 604.0           | 31.25            | 27.78           |
| ZRO2-B1-5               | 33.07      | 23.77      | 5.73         | 8.04              | 4.65             | 18.83       | 6.022                           | 1387.9      | 575.5           | 32.22            | 16.06           |
| ZRO2-B1-6               | 33.05      | 23.82      | 5.83         | 8.06              | 4.62             | 18.87       | 6.069                           | 1362.9      | 573.5           | 33.05            | 10.16           |
| ZRO2-B1-7               | 33.05      | 23.84      | 5.80         | 8.05              | 4.61             | 18.88       | 6.089                           | 961.1       | 407.0           | 32.92            | 0.06            |
| ZRO2-B1-8               | 33.05      | 23.86      | 5.78         | 8.05              | 4.60             | 18.87       | 6.095                           | 1432.9      | 609.9           | 32.47            | 11.43           |
| ZRO2-B1-9               | 33.07      | 23.84      | 5.82         | 8.05              | 4.62             | 18.85       | 6.065                           | 1395.0      | 588.2           | 32.68            | 7.48            |
| ZRO2-B2-1               | 33.05      | 23.86      | 5.72         | 8.05              | 4.60             | 18.83       | 6.078                           | 1384.0      | 589.1           | 32.73            | 5.99            |
| ZRO2-B2-2               | 33.06      | 23.85      | 5.70         | 8.05              | 4.61             | 18.83       | 6.063                           | 1406.7      | 595.9           | 32.22            | 15.96           |
| ZRO2-B2-3               | 33.06      | 23.81      | 5.70         | 8.02              | 4.63             | 18.87       | 6.077                           | 1273.6      | 536.0           | 32.70            | 7.00            |
| ZRO2-B2-4               | 33.06      | 23.83      | 5.77         | 8.05              | 4.62             | 18.88       | 6.073                           | 1177.2      | 496.1           | 32.24            | 15.52           |
| ZRO2-B2-5               | 33.06      | 23.93      | 5.76         | 8.05              | 4.57             | 18.86       | 6.121                           | 1438.7      | 622.1           | 31.48            | 25.54           |
| ZRO2-B2-6               | 33.05      | 23.87      | 5.70         | 8.07              | 4.59             | 18.89       | 6.086                           | 1478.0      | 629.1           | 32.92            | 0.24            |
| ZRO2-B2-7               | 33.05      | 23.90      | 5.75         | 8.06              | 4.58             | 18.86       | 6.104                           | 1462.2      | 628.0           | 33.05            | 10.02           |
| ZRO2-B2-8               | 33.06      | 23.90      | 5.79         | 8.02              | 4.58             | 18.81       | 6.113                           | 1404.3      | 604.8           | 33.01            | 3.78            |
| ZRO2-B2-9               | 33.06      | 23.83      | 5.74         | 8.05              | 4.62             | 18.88       | 6.071                           | 1419.4      | 598.2           | 33.02            | 4.36            |
| m = 9.34                |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| sigma_theta = 607.3 MPa |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| sigma_avg = 580.8 MPa   |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| std dev = 56.3 MPa      |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |

Table A-1.3. C-ring data for Saint-Gobain enhanced hexoloy SA (SCEH).

| Specimen                | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | $\theta$<br>(°) |
|-------------------------|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|-----------------|
| SCEH-B5-1               | 33.09      | 23.82      | 5.72         | 8.10              | 4.64             | 9.73        | 3.094                           | 771.1       | 320.1           | 32.09            | 18.29           |
| SCEH-B5-2               | 33.07      | 23.88      | 5.72         | 8.10              | 4.60             | 9.70        | 3.109                           | 691.6       | 292.8           | 32.57            | 9.99            |
| SCEH-B5-3               | 33.06      | 23.92      | 5.72         | 8.09              | 4.57             | 9.70        | 3.128                           | 575.6       | 247.0           | 30.54            | 35.07           |
| SCEH-B5-4               | 33.07      | 23.87      | 5.68         | 7.91              | 4.60             | 9.48        | 3.108                           | 751.4       | 324.9           | 30.89            | 31.95           |
| SCEH-B5-5               | 33.08      | 23.85      | 5.68         | 8.00              | 4.62             | 9.58        | 3.095                           | 825.8       | 350.5           | 32.79            | 5.30            |
| SCEH-B5-6               | 33.08      | 23.88      | 5.70         | 8.08              | 4.60             | 9.70        | 3.112                           | 792.3       | 335.5           | 31.50            | 25.64           |
| SCEH-B5-7               | 33.08      | 23.83      | 5.75         | 8.09              | 4.63             | 9.70        | 3.096                           | 690.4       | 288.3           | 32.32            | 14.60           |
| SCEH-B5-8               | 33.08      | 23.82      | 5.64         | 8.10              | 4.63             | 9.73        | 3.095                           | 856.2       | 356.2           | 32.62            | 9.32            |
| SCEH-B5-9               | 33.08      | 23.83      | 5.67         | 8.09              | 4.63             | 9.71        | 3.097                           | 818.3       | 341.7           | 32.46            | 12.35           |
| SCEH-B6-1               | 32.94      | 23.93      | 5.65         | 8.09              | 4.51             | 9.51        | 3.115                           | 366.3       | 161.8           | 32.81            | 0.31            |
| SCEH-B6-2               | 32.94      | 23.93      | 5.69         | 8.09              | 4.51             | 9.51        | 3.117                           | 856.1       | 378.2           | 32.64            | 5.53            |
| SCEH-B6-3               | 32.96      | 23.90      | 5.73         | 8.00              | 4.53             | 9.39        | 3.097                           | 699.2       | 308.5           | 32.16            | 15.29           |
| SCEH-B6-4               | 32.95      | 23.91      | 5.74         | 8.09              | 4.52             | 9.49        | 3.102                           | 656.8       | 288.0           | 31.72            | 21.38           |
| SCEH-B6-5               | 32.96      | 23.91      | 5.63         | 8.10              | 4.53             | 9.55        | 3.110                           | 765.8       | 334.6           | 32.65            | 5.89            |
| SCEH-B6-6               | 32.99      | 23.91      | 5.75         | 8.06              | 4.54             | 9.49        | 3.100                           | 463.0       | 202.2           | 31.62            | 23.04           |
| SCEH-B6-7               | 32.94      | 23.91      | 5.77         | 8.09              | 4.52             | 9.49        | 3.107                           | 470.4       | 206.7           | 31.03            | 29.13           |
| SCEH-B6-8               | 32.95      | 23.96      | 5.69         | 8.10              | 4.50             | 9.46        | 3.101                           | 651.9       | 289.2           | 32.17            | 15.04           |
| SCEH-B6-9               | 32.97      | 23.94      | 5.67         | 8.02              | 4.52             | 9.65        | 3.180                           | 804.6       | 357.1           | 32.86            | 0.54            |
| m = 4.63                |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| sigma_theta = 323.2 MPa |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| sigma_avg = 299.1 MPa   |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| std dev = 59.9 MPa      |            |            |              |                   |                  |             |                                 |             |                 |                  |                 |

Table A-1.4. C-ring data for Saint-Gobain liquid phase sintered hexoloy SA (SCLH).

| Specimen   | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | θ<br>(°) |
|--|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|----------|
| SCLH-B1-1  | 32.97      | 23.95      | 5.62         | 8.01              | 4.51             | 9.30        | 3.070                           | 885.0       | 394.3           | 32.92            | 3.50     |
| SCLH-B1-2  | 32.97      | 23.89      | 5.64         | 8.10              | 4.54             | 9.42        | 3.058                           | 831.7       | 360.8           | 32.45            | 10.53    |
| SCLH-B1-3  | 32.98      | 23.90      | 5.69         | 8.02              | 4.54             | 9.35        | 3.067                           | 637.9       | 279.6           | 32.59            | 7.71     |
| SCLH-B1-4  | 32.98      | 23.73      | 5.63         | 8.04              | 4.63             | 9.32        | 3.001                           | 789.2       | 330.2           | 32.30            | 13.48    |
| SCLH-B1-5  | 32.98      | 23.81      | 5.73         | 8.05              | 4.59             | 9.44        | 3.061                           | 781.0       | 333.2           | 32.70            | 4.94     |
| SCLH-B1-6  | 32.98      | 23.90      | 5.60         | 7.99              | 4.54             | 9.29        | 3.055                           | 825.7       | 363.2           | 32.61            | 7.40     |
| SCLH-B1-7  | 32.98      | 23.84      | 5.68         | 8.00              | 4.57             | 9.29        | 3.038                           | 663.0       | 286.8           | 32.12            | 16.31    |
| SCLH-B1-8  | 32.98      | 23.86      | 5.65         | 8.10              | 4.56             | 9.40        | 3.040                           | 709.1       | 304.5           | 32.20            | 15.11    |
| SCLH-B1-9  | 32.97      | 23.80      | 5.60         | 8.04              | 4.59             | 9.37        | 3.039                           | 722.2       | 308.3           | 32.87            | 0.85     |
| SCLH-B2-1  | 33.04      | 23.82      | 5.60         | 8.10              | 4.61             | 9.48        | 3.030                           | 652.5       | 273.8           | 32.15            | 16.90    |
| SCLH-B2-2  | 33.04      | 23.80      | 5.65         | 8.08              | 4.62             | 9.41        | 3.011                           | 858.6       | 359.3           | 32.83            | 3.08     |
| SCLH-B2-3  | 33.03      | 23.86      | 5.66         | 8.09              | 4.59             | 9.52        | 3.063                           | 872.7       | 371.2           | 32.38            | 12.90    |
| SCLH-B2-4  | 33.04      | 23.82      | 5.65         | 8.08              | 4.61             | 9.40        | 3.013                           | 737.9       | 310.4           | 32.85            | 2.45     |
| SCLH-B2-5  | 33.03      | 23.87      | 5.66         | 8.07              | 4.58             | 9.38        | 3.029                           | 616.0       | 263.3           | 32.28            | 14.60    |
| SCLH-B2-6  | 33.03      | 23.85      | 5.66         | 8.08              | 4.59             | 9.42        | 3.032                           | 818.0       | 347.5           | 32.44            | 11.82    |
| SCLH-B2-7  | 33.04      | 23.81      | 5.65         | 8.09              | 4.62             | 9.40        | 3.007                           | 812.4       | 340.4           | 31.58            | 24.35    |
| SCLH-B2-8  | 33.03      | 23.83      | 5.65         | 8.08              | 4.60             | 9.42        | 3.026                           | 725.1       | 306.4           | 32.15            | 16.66    |
| SCLH-B2-9  | 33.03      | 23.84      | 5.68         | 8.07              | 4.60             | 9.39        | 3.024                           | 726.2       | 308.1           | 32.25            | 15.05    |
| m = 9.55<br>sigma_theta = 344.4 MPa<br>sigma_avg = 330.1 MPa<br>std dev = 37.3 MPa |            |            |              |                   |                  |             |                                 |             |                 |                  |          |

Table A-1.5. C-ring strength data for ceradyne ceralloy 146-5S (SC46).

| Specimen  | Do<br>(mm)          | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | $\theta$<br>(°) |
|---|---------------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|-----------------|
| SC46-B1-1   | 33.05               | 23.83      | 5.68         | 8.07              | 4.61             | 9.64        | 3.094                           | 635.3       | 267.7           | 32.19            | 16.30           |
| SC46-B1-2   | 33.05               | 23.84      | 5.69         | 8.05              | 4.61             | 9.64        | 3.105                           | 593.7       | 251.4           | 32.78            | 4.74            |
| SC46-B1-3   | 33.05               | 23.80      | 5.69         | 8.05              | 4.63             | 9.65        | 3.097                           | 710.4       | 297.8           | 32.40            | 12.85           |
| SC46-B1-4   | 33.05               | 23.86      | 5.68         | 8.05              | 4.60             | 9.65        | 3.113                           | 689.2       | 293.3           | 32.59            | 9.25            |
| SC46-B1-5   | 33.04               | 23.82      | 5.71         | 8.07              | 4.61             | 9.65        | 3.100                           | 634.7       | 267.3           | 32.31            | 14.18           |
| SC46-B1-6   | 33.05               | 23.85      | 5.71         | 8.06              | 4.60             | 9.66        | 3.111                           | 545.7       | 231.4           | 32.44            | 12.10           |
| SC46-B1-7   | 33.04               | 23.93      | 5.68         | 8.07              | 4.56             | 9.65        | 3.129                           | 615.4       | 266.6           | 31.84            | 21.08           |
| SC46-B1-8   | 33.04               | 23.77      | 5.68         | 8.07              | 4.64             | 9.67        | 3.091                           | 597.8       | 248.6           | 32.91            | 0.27            |
| SC46-B1-9   | BROKEN UPON RECEIPT |            |              |                   |                  |             |                                 |             |                 |                  |                 |
| SC46-B1-10  | 33.06               | 23.77      | 5.68         | 8.07              | 4.65             | 9.66        | 3.080                           | 597.8       | 247.5           | 32.91            | 1.03            |
| SC46-B2-1   | 33.05               | 23.78      | 5.70         | 8.01              | 4.64             | 9.47        | 3.049                           | 661.3       | 277.1           | 32.40            | 12.83           |
| SC46-B2-2   | 33.04               | 23.93      | 5.71         | 8.05              | 4.56             | 9.52        | 3.096                           | 714.4       | 310.3           | 32.08            | 17.74           |
| SC46-B2-3   | 33.04               | 23.84      | 5.69         | 8.06              | 4.60             | 9.53        | 3.070                           | 694.2       | 294.2           | 32.79            | 4.19            |
| SC46-B2-4   | 33.04               | 23.88      | 5.74         | 8.05              | 4.58             | 9.52        | 3.083                           | 705.1       | 302.3           | 32.94            | 1.09            |
| SC46-B2-5   | 33.05               | 23.73      | 5.69         | 8.05              | 4.66             | 9.53        | 3.040                           | 707.4       | 291.3           | 32.98            | 2.45            |
| SC46-B2-6   | 33.04               | 23.78      | 5.69         | 8.05              | 4.63             | 9.53        | 3.057                           | 687.4       | 287.3           | 32.42            | 12.32           |
| SC46-B2-7   | 33.04               | 23.87      | 5.68         | 8.06              | 4.59             | 9.53        | 3.078                           | 653.9       | 279.3           | 32.67            | 7.27            |
| SC46-B2-8   | 33.04               | 23.81      | 5.67         | 8.05              | 4.62             | 9.52        | 3.061                           | 649.0       | 273.3           | 32.97            | 2.42            |
| SC46-B2-9   | 33.04               | 23.90      | 5.68         | 8.05              | 4.57             | 9.53        | 3.090                           | 639.6       | 275.6           | 32.40            | 12.69           |
| m = 14.42<br>sigma_theta = 284.5 MPa<br>sigma_avg = 276.2 MPa<br>std dev = 20.7 MPa |                     |            |              |                   |                  |             |                                 |             |                 |                  |                 |

Table A-1.6. C-ring strength data for ceradyne ceralloy 147-31N (SN47).

| Specimen      | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | θ<br>(°) |
|---------------|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|----------|
| SN47-B1-1     | 33.04      | 23.87      | 5.71         | 8.04              | 4.59             | 9.85        | 3.212                           | 1791.9      | 767.3           | 31.87            | 20.63    |
| SN47-B1-2     | 33.02      | 23.90      | 5.70         | 8.05              | 4.56             | 9.87        | 3.231                           | 1703.2      | 737.2           | 32.45            | 11.38    |
| SN47-B1-3     | 33.01      | 23.81      | 5.73         | 8.06              | 4.60             | 9.87        | 3.206                           | 1717.6      | 727.1           | 32.5             | 10.17    |
| SN47-B1-4     | 33.05      | 23.84      | 5.70         | 8.07              | 4.61             | 9.88        | 3.197                           | 2040.1      | 861.7           | 32.23            | 15.65    |
| SN47-B1-5     | 33.05      | 23.90      | 5.73         | 8.06              | 4.58             | 9.86        | 3.213                           | 1752.2      | 752.6           | 32.93            | 0.22     |
| SN47-B1-6     | 33.08      | 23.90      | 5.78         | 8.06              | 4.59             | 9.87        | 3.206                           | 1851.3      | 790.0           | 33.04            | 4.43     |
| SN47-B1-7     | 33.05      | 23.90      | 5.74         | 8.05              | 4.58             | 9.88        | 3.224                           | 1742.3      | 749.2           | 32.47            | 11.50    |
| SN47-B1-8     | 33.05      | 23.90      | 5.73         | 8.05              | 4.58             | 9.86        | 3.217                           | 1804.9      | 776.2           | 31.52            | 25.02    |
| SN47-B2-1     | 33.05      | 23.90      | 5.69         | 8.06              | 4.58             | 9.87        | 3.214                           | 1826.8      | 784.6           | 32.6             | 9.02     |
| SN47-B2-2     | 33.05      | 23.90      | 5.69         | 8.04              | 4.58             | 9.87        | 3.222                           | 1918.3      | 826.0           | 32.32            | 14.22    |
| SN47-B2-3     | 33.05      | 23.89      | 5.69         | 8.05              | 4.58             | 9.86        | 3.212                           | 1733.1      | 743.4           | 32.68            | 7.25     |
| SN47-B2-4     | 33.05      | 23.90      | 5.69         | 8.07              | 4.58             | 9.87        | 3.210                           | 1756.1      | 753.3           | 32.72            | 6.29     |
| SN47-B2-5     | 33.05      | 23.90      | 5.70         | 8.05              | 4.58             | 9.87        | 3.219                           | 1665.6      | 716.3           | 32.8             | 4.17     |
| SN47-B2-6     | 33.05      | 23.86      | 5.69         | 8.06              | 4.60             | 9.87        | 3.203                           | 1639.5      | 697.0           | 31.94            | 19.87    |
| SN47-B2-7     | 33.06      | 23.88      | 5.69         | 8.05              | 4.59             | 9.87        | 3.208                           | 1836.3      | 783.9           | 31.9             | 20.53    |
| SN47-B2-8     | 33.06      | 23.91      | 5.70         | 8.06              | 4.58             | 9.86        | 3.210                           | 1796.8      | 772.0           | 32.35            | 13.86    |
| SN47-B2-9     | 33.05      | 23.88      | 5.71         | 8.06              | 4.59             | 9.87        | 3.209                           | 1666.5      | 712.1           | 32.31            | 14.35    |
| SN47-B2-10    | 33.06      | 23.88      | 5.73         | 8.06              | 4.59             | 9.87        | 3.206                           | 1403.6      | 598.5           | 32.99            | 2.52     |
| m =           | 13.70      |            |              |                   |                  |             |                                 |             |                 |                  |          |
| sigma_theta = | 776.5      | MPa        |              |                   |                  |             |                                 |             |                 |                  |          |
| sigma_avg =   | 752.7      | MPa        |              |                   |                  |             |                                 |             |                 |                  |          |
| std dev =     | 55.6       | MPa        |              |                   |                  |             |                                 |             |                 |                  |          |

Table A-1.7. C-ring strength data for kennametal TK4 SiAlON (STK4).

| Specimen              | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) | Break, b<br>(mm) | θ<br>(°) |
|-----------------------|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|------------------|----------|
| STK4-B1-1             | 33.15      | 23.91      | 6.22         | 7.98              | 4.62             | 10.2241     | 3.321                           | 2022.20     | 860.7           | —                | 169.19   |
| STK4-B1-2             | 33.14      | 23.89      | 6.24         | 8.15              | 4.63             | 10.2733     | 3.266                           | 2021.64     | 840.1           | —                | 169.15   |
| STK4-B1-3             | 33.12      | 23.90      | 6.23         | 8.02              | 4.61             | 10.2490     | 3.322                           | 1863.19     | 792.2           | —                | 169.16   |
| STK4-B1-4             | 33.10      | 23.91      | 6.25         | 8.12              | 4.60             | 10.2660     | 3.299                           | 2181.78     | 922.5           | —                | 169.12   |
| STK4-B1-5             | 33.10      | 23.89      | 6.23         | 8.05              | 4.61             | 10.2748     | 3.324                           | 887.00      | 376.4           | 33.03            | 3.39     |
| STK4-B1-6             | 33.11      | 23.91      | 6.24         | 8.07              | 4.60             | 10.2312     | 3.303                           | 1018.98     | 432.6           | 31.57            | 24.22    |
| STK4-B1-7             | 33.10      | 23.91      | 6.24         | 8.07              | 4.60             | 10.2367     | 3.309                           | 1355.62     | 576.7           | 32.29            | 14.54    |
| STK4-B1-8             | 33.11      | 23.91      | 6.23         | 8.05              | 4.60             | 10.2779     | 3.326                           | 969.92      | 412.8           | 30.74            | 32.77    |
| STK4-B1-9             | 33.11      | 23.91      | 6.24         | 8.11              | 4.60             | 10.2707     | 3.300                           | 2012.67     | 850.2           | 28.39            | 51.08    |
| STK4-B3-1             | 33.11      | 23.88      | 6.24         | 8.07              | 4.62             | 10.3150     | 3.321                           | 1399.07     | 589.4           |                  | 169.14   |
| STK4-B3-2             | 33.13      | 23.90      | 6.24         | 8.10              | 4.62             | 10.3309     | 3.312                           | 1665.07     | 699.4           | 31.03            | 30.16    |
| STK4-B3-3             | 33.10      | 23.89      | 6.25         | 8.12              | 4.61             | 10.3297     | 3.313                           | 1436.44     | 604.3           | 31.51            | 24.78    |
| STK4-B3-4             | 33.11      | 23.90      | 6.26         | 8.12              | 4.61             | 10.3171     | 3.308                           | 1997.36     | 840.6           | —                | 169.10   |
| STK4-B3-5             | 33.11      | 23.90      | 6.24         | 8.12              | 4.61             | 10.3145     | 3.307                           | 2011.16     | 846.4           | —                | 169.14   |
| STK4-B3-6             | 33.12      | 23.88      | 6.25         | 8.17              | 4.62             | 10.3083     | 3.275                           | 1632.17     | 677.7           | 31.79            | 21.71    |
| STK4-B3-7             | 33.12      | 23.89      | 6.24         | 8.06              | 4.62             | 10.3174     | 3.325                           | 1586.02     | 669.3           | 28.13            | 52.86    |
| STK4-B3-8             | 33.12      | 23.91      | 6.25         | 8.02              | 4.61             | 10.2627     | 3.330                           | 1774.58     | 756.4           | —                | 169.12   |
| STK4-B3-9             | 33.12      | 23.91      | 6.24         | 8.07              | 4.61             | 10.3253     | 3.329                           | 1756.80     | 744.2           | —                | 169.14   |
| m = —                 |            |            |              |                   |                  |             |                                 |             |                 |                  |          |
| sigma_theta = — MPa   |            |            |              |                   |                  |             |                                 |             |                 |                  |          |
| sigma_avg = 694.0 MPa |            |            |              |                   |                  |             |                                 |             |                 |                  |          |
| std dev = 166.0 MPa   |            |            |              |                   |                  |             |                                 |             |                 |                  |          |



Table A-1.8. C-ring strength data for kyocera SN235P (SN5P).

| Specimen  | Do<br>(mm) | Di<br>(mm) | Slot<br>(mm) | Height, b<br>(mm) | Width, t<br>(mm) | Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Load<br>(N) | Stress<br>(MPa) |
|-----------|------------|------------|--------------|-------------------|------------------|-------------|---------------------------------|-------------|-----------------|
| SN5P-B1-1 | 33.06      | 24.01      | 6.28         | 7.988             | 4.53             | 9.7369      | 3.19                            | 1528.51     | 680.1           |
| SN5P-B1-2 | 33.05      | 24.00      | 6.30         | 7.986             | 4.53             | 9.7492      | 3.19                            | 1263.60     | 562.1           |
| SN5P-B1-3 | 33.06      | 24.02      | 6.29         | 8.011             | 4.52             | 9.7735      | 3.19                            | 1584.87     | 704.9           |
| SN5P-B1-4 | 33.06      | 24.04      | 6.29         | 8.002             | 4.51             | 9.7685      | 3.20                            | 1560.66     | 698.6           |
| SN5P-B1-5 | 33.05      | 24.03      | 6.29         | 8.016             | 4.51             | 9.7624      | 3.19                            | 1421.66     | 635.0           |
| SN5P-B1-6 | 33.05      | 24.04      | 6.29         | 7.992             | 4.51             | 9.7574      | 3.20                            | 1620.42     | 727.8           |
| SN5P-B1-7 | 33.04      | 24.02      | 6.30         | 8.010             | 4.51             | 9.7669      | 3.20                            | 1574.84     | 703.6           |
| SN5P-B1-8 | 33.04      | 24.03      | 6.28         | 7.990             | 4.51             | 9.7491      | 3.20                            | 1508.65     | 677.5           |
| SN5P-B1-9 | 33.05      | 24.06      | 6.29         | 8.017             | 4.50             | 9.7829      | 3.21                            | 1061.61     | 477.8           |
| SN5P-B2-1 | 33.02      | 24.00      | 6.30         | 7.999             | 4.51             | 9.7564      | 3.20                            | 1544.07     | 690.3           |
| SN5P-B2-2 | 33.01      | 24.03      | 6.35         | 7.999             | 4.49             | 9.7381      | 3.21                            | 1586.05     | 716.2           |
| SN5P-B2-3 | 33.02      | 24.03      | 6.33         | 7.977             | 4.50             | 9.6947      | 3.20                            | 1191.86     | 538.5           |
| SN5P-B2-4 | 33.02      | 24.02      | 6.26         | 7.999             | 4.50             | 9.7511      | 3.20                            | 1418.12     | 637.3           |
| SN5P-B2-5 | 33.00      | 24.07      | 6.27         | 7.996             | 4.47             | 9.6947      | 3.21                            | 1525.72     | 698.0           |
| SN5P-B2-6 | 33.02      | 24.01      | 6.27         | 7.994             | 4.51             | 9.7422      | 3.20                            | 1570.55     | 704.4           |
| SN5P-B2-7 | 33.02      | 24.03      | 6.27         | 8.007             | 4.50             | 9.7604      | 3.21                            | 1200.18     | 540.2           |
| SN5P-B2-8 | 33.03      | 24.00      | 6.28         | 7.999             | 4.52             | 9.7537      | 3.20                            | 1680.23     | 749.5           |
| SN5P-B2-9 | 33.04      | 24.00      | 6.28         | 7.998             | 4.52             | 9.7549      | 3.19                            | 1413.05     | 629.0           |
| Average   |            |            |              |                   |                  |             | 3.20                            | 1458.59     | 653.94          |
| Std. dev. |            |            |              |                   |                  |             | 0.01                            | 171.81      | 76.52           |

## A-2. Room Temperature Uniaxial Tensile Strength Data

Table A-2.1. Tensile test results; CoorsTek AD 995 (ALOX); 25 October 2002.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|-----------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                 |                       |
| 10              | 0.2500        | 1803      | 36.7             | 253   | Surface @ pit   | 28                    |
| 13              | 0.2506        | 1987      | 40.3             | 278   | Volume @ void   | 30                    |
| 5               | 0.2505        | 2038      | 41.4             | 285   | Surface         | 30                    |
| 6               | 0.2502        | 2111      | 42.9             | 296   | Surface         | 30                    |
| 17              | 0.2502        | 2127      | 43.3             | 298   | Surface         | 30                    |
| 14              | 0.2498        | 2150      | 43.9             | 302   | Surface         | 54                    |
| 16              | 0.2504        | 2191      | 44.5             | 307   | Surface         | 30                    |
| 18              | 0.2500        | 2212      | 45.1             | 311   | Volume          | 28                    |
| 3               | 0.2505        | 2260      | 45.9             | 316   | Volume          | 28                    |
| 4               | 0.2505        | 2274      | 46.1             | 318   | Volume          | 31                    |
| 2               | 0.2505        | 2304      | 46.7             | 322   | Volume          | 54                    |
| 20              | 0.2498        | 2296      | 46.8             | 323   | Volume          | 54                    |
| 7               | 0.2505        | 2328      | 47.2             | 326   | Volume          | 37                    |
| 11              | 0.2504        | 2333      | 47.4             | 327   | Volume          | 29                    |
| 15              | 0.2500        | 2345      | 47.8             | 329   | Volume          | 29                    |
| 8               | 0.2502        | 2351      | 47.8             | 330   | Surface         | 29                    |
| 12              | 0.2506        | 2370      | 48.1             | 331   | Volume          | 28                    |
| 9               | 0.2502        | 2383      | 48.5             | 334   | Surface         | 30                    |
| 19              | 0.2504        | 2408      | 48.9             | 337   | Surface         | 37                    |
| 1               | 0.2504        | 2532      | 51.4             | 355   | Volume          | 30                    |
|                 |               | Average   | 45.5             | 314   |                 |                       |
|                 |               | Std. dev. | 3.4              | 23    |                 |                       |

Notes: Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips.

Table A-2.2. Tensile test results; CoorsTek Ce-TZP (ZRO<sub>2</sub>); 06 November 2002.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin      | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|----------------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                      |                       |
| 14              | 0.2493        | 3073      | 63.0             | 434   | Surface              | 24                    |
| 4               | 0.2502        | 3390      | 68.9             | 475   | Surface              | 25                    |
| 17              | 0.2619        | 3737      | 69.4             | 478   | Volume               | 26                    |
| 13              | 0.2498        | 3730      | 76.1             | 525   | Volume @ void        | 31                    |
| 15              | 0.2497        | 3787      | 77.3             | 533   | Surface              | 24                    |
| 19              | 0.2499        | 3937      | 80.3             | 553   | Surface              | 32                    |
| 12              | 0.2483        | 3904      | 80.6             | 556   | Volume @ void        | 31                    |
| 6               | 0.2503        | 4011      | 81.5             | 562   | Volume @ void        | 24                    |
| 3               | 0.2497        | 4019      | 82.1             | 566   | Surface              | 24                    |
| 10              | 0.2491        | 4007      | 82.2             | 567   | Volume               | 25                    |
| 9               | 0.2492        | 4025      | 82.5             | 569   | Volume @ agglomerate | 30                    |
| 1               | 0.2498        | 4053      | 82.7             | 570   | Volume               | 30                    |
| 8               | 0.2494        | 4069      | 83.3             | 574   | Volume @ void        | 27                    |
| 20              | 0.2499        | 4114      | 83.9             | 578   | Volume               | 25                    |
| 16              | 0.2494        | 4108      | 84.1             | 580   | Surface              | 29                    |
| 5               | 0.2503        | 4151      | 84.4             | 582   | Volume @ void        | 24                    |
| 18              | 0.2491        | 4124      | 84.6             | 583   | Surface              | 27                    |
| 11              | 0.2493        | 4145      | 84.9             | 585   | Surface @ inclusion  | 31                    |
| 2               | 0.2501        | 4241      | 86.3             | 595   | Surface @ pit        | 31                    |
| 7               | 0.2492        | 4283      | 87.8             | 605   | Surface              | 25                    |
|                 |               | Average   | 80.3             | 554   |                      |                       |
|                 |               | Std. dev. | 6.4              | 44    |                      |                       |

Notes: Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips.

Specimen 17 failed in the top transition region.

Specimen 9 failed at agglomerate that was recovered and analyzed. The agglomerate was found to be aluminum oxide. When the agglomerate was removed the fracture surface looked like the volume at void fracture initiation sites.

Table A-2.3. Tensile test results; carborundum liquid phase sintered hexoloy SA (SCLH); 15 November 2002.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|-----------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                 |                       |
| A-19            | 0.2499        | 1335      | 27.2             | 188   | Volume          | 20                    |
| A-17            | 0.2501        | 1743      | 35.5             | 245   | Surface @ pit   | 48                    |
| A-3             | 0.2502        | 1852      | 37.7             | 260   | Volume          | 23                    |
| A-4             | 0.2483        | 1826      | 37.7             | 260   | Surface         | 27                    |
| A-5             | 0.2501        | 1962      | 39.9             | 275   | Surface         | 28                    |
| A-16            | 0.2499        | 2014      | 41.1             | 283   | Volume @ pore   | 21                    |
| A-6             | 0.2499        | 2054      | 41.9             | 289   | Volume @ pore   | 28                    |
| A-20            | 0.2521        | 2101      | 42.1             | 290   | Volume @ pore   | 29                    |
| A-9             | 0.2492        | 2087      | 42.8             | 295   | Volume @ pore   | 48                    |
| A-7             | 0.2498        | 2120      | 43.3             | 298   | Volume @ pore   | 21                    |
| A-12            | 0.2501        | 2137      | 43.5             | 300   | Volume @ pore   | 44                    |
| A-13            | 0.2500        | 2137      | 43.5             | 300   | Volume          | 46                    |
| A-8             | 0.2501        | 2139      | 43.5             | 300   | Surface         | 38                    |
| A-18            | 0.2501        | 2156      | 43.9             | 303   | Volume @ pore   | 21                    |
| A-11            | 0.2494        | 2170      | 44.4             | 306   | Surface         | 22                    |
| A-2             | 0.2496        | 2183      | 44.6             | 308   | Surface         | 20                    |
| A-10            | 0.2501        | 2202      | 44.8             | 309   | Volume @ pore   | 23                    |
| A-15            | 0.2501        | 2234      | 45.5             | 314   | Volume @ pore   | 23                    |
| A-1             | 0.2495        | 2264      | 46.3             | 319   | Volume          | 21                    |
|                 |               | Average   | 41.5             | 286   |                 |                       |
|                 |               | Std. dev. | 4.5              | 31    |                 |                       |

Notes: Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips

Specimen A-14 was not suitable for testing due to its irregular shape.

Specimen A-20 failed in the upper transition region.

Specimen A-4 had a large undercut in the top shank.

Specimens A-8 and A-18 had scuff marks in the shank.

Table A-2.4. Tensile test results; Ceradyne 146-5S (SC46); 15 November 2002.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin  | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|------------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                  |                       |
| 13              | 0.2502        | 1573      | 32.0             | 221   | Volume           | 28                    |
| 3               | 0.2501        | 1845      | 37.6             | 259   | Surface @ pit    | 29                    |
| 12              | 0.2475        | 1887      | 39.2             | 270   | Volume           | 30                    |
| 7               | 0.2503        | 1986      | 40.4             | 278   | Surface          | 30                    |
| 5               | 0.2506        | 1995      | 40.4             | 279   | Surface          | 26                    |
| 8               | 0.2499        | 2031      | 41.4             | 286   | Surface          | 26                    |
| 4               | 0.2498        | 2048      | 41.8             | 288   | Volume @ pullout | 26                    |
| 16              | 0.2492        | 2047      | 42.0             | 289   | Surface          | 27                    |
| 11              | 0.2493        | 2066      | 42.3             | 292   | Surface          | 29                    |
| 10              | 0.2497        | 2092      | 42.7             | 295   | Surface          | 29                    |
| 1               | 0.2499        | 2126      | 43.3             | 299   | Surface          | 29                    |
| 9               | 0.2500        | 2143      | 43.7             | 301   | Volume           | 28                    |
| 15              | 0.2499        | 2146      | 43.8             | 302   | Surface @ pit    | 26                    |
| 6               | 0.2502        | 2152      | 43.8             | 302   | Volume           | 29                    |
| 2               | 0.2503        | 2178      | 44.3             | 305   | Surface          | 26                    |
|                 |               | Average   | 41.2             | 284   |                  |                       |
|                 |               | Std. dev. | 3.2              | 22    |                  |                       |

Notes: Ceradyne 146-5S (SC46).

Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips.

Specimen A-20 failed in the upper transition region.

Table A-2.5. Tensile test results; Ceradyne Ceralloy 147-31N (SN47); 23 October 2002.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|-----------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                 |                       |
| 14              | 0.2631        | 4295      | 79.0             | 545   | Volume          | 40                    |
| 11              | 0.2505        | 3916      | 79.5             | 548   | Surface         | 55                    |
| 16              | 0.2504        | 3930      | 79.8             | 550   | Volume          | 55                    |
| 10              | 0.2673        | 4501      | 80.2             | 553   | Surface         | 55                    |
| 12              | 0.2460        | 4316      | 90.8             | 626   | Volume          | 36                    |
| 20              | 0.2504        | 5294      | 107.5            | 741   | Surface         | 58                    |
| 17              | 0.2561        | 5560      | 107.9            | 744   | Surface         | 55                    |
| 15              | 0.2506        | 5549      | 112.5            | 776   | Surface         | 55                    |
| 18              | 0.2506        | 5572      | 113.0            | 779   | Volume          | 40                    |
| 4               | 0.2506        | 5601      | 113.6            | 783   | Surface         | 55                    |
| 9               | 0.2505        | 5655      | 114.7            | 791   | Volume          | 55                    |
| 1               | 0.2503        | 5717      | 116.2            | 801   | Surface         | 55                    |
| 6               | 0.2506        | 5807      | 117.7            | 812   | Volume          | 40                    |
| 3               | 0.2505        | 6008      | 121.9            | 841   | Surface         | 40                    |
| 13              | 0.2507        | 6068      | 122.9            | 848   | Volume          | 40                    |
| 2               | 0.2492        | 6102      | 125.1            | 863   | Surface         | 55                    |
| 8               | 0.2483        | 6236      | 128.8            | 888   | Volume          | 58                    |
| 7               | 0.2501        | 6342      | 129.1            | 890   | Volume          | 55                    |
| 19              | 0.2502        | 6438      | 130.9            | 903   | Volume          | 55                    |
| 5               | 0.2500        | 6452      | 131.4            | 906   | Volume          | 57                    |
|                 |               | Average   | 110.1            | 759   |                 |                       |
|                 |               | Std. dev. | 18.3             | 126   |                 |                       |

Notes: Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips.

No fracture origin could be positively identified for specimen 6.

Specimens 17 and 14 failed in the top transition region. Specimen 1 failed at or very near the top transition region.

Specimen 10 failed in the bottom transition region. Specimen 4 failed at or very near the bottom transition region.

Table A-2.6. Tensile test results; Kennametal STK-4 SiAlON (STK4); 19 December 2002.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin          | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|--------------------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                          |                       |
| A-8             | 0.2504        | 3228      | 65.6             | 452   | Volume @ inclusion       | 19                    |
| A-16            | 0.2574        | 3392      | 65.2             | 449   | Surface @ inclusion      | 19                    |
| A-19            | 0.2500        | 3652      | 74.4             | 513   | Volume @ inclusion       | 22                    |
| A-1             | 0.2704        | 2815      | 49.0             | 338   | Volume @ inclusion       | 22                    |
| A-15            | 0.2503        | 3285      | 66.8             | 460   | Volume @ inclusion       | 23                    |
| A-12            | 0.2502        | 2162      | 44.0             | 303   | Volume @ inclusion       | 24                    |
| A-3             | 0.2501        | 2554      | 52.0             | 358   | Volume @ inclusion       | 24                    |
| A-17            | 0.2500        | 3686      | 75.1             | 518   | Volume @ inclusion       | 24                    |
| A-23            | 0.2501        | 3285      | 66.9             | 461   | Volume @ inclusion       | 25                    |
| A-10            | 0.2506        | 3717      | 75.4             | 520   | Volume @ inclusion       | 27                    |
| A-14            | 0.2753        | 2537      | 42.6             | 294   | Surface @ radial scratch | 27                    |
| A-22            | 0.2504        | 3043      | 61.8             | 426   | Volume @ inclusion       | 25                    |
| A-9             | 0.2909        | 3266      | 49.1             | 339   | Surface @ inclusion      | 27                    |
| A-20            | 0.2502        | 3113      | 63.3             | 437   | Surface                  | 27                    |
| A-7             | 0.2501        | 2649      | 53.9             | 372   | Volume @ inclusion       | 27                    |
| A-18            | 0.2501        | 3246      | 66.1             | 456   | Volume @ inclusion       | 37                    |
| A-13            | 0.2505        | 3586      | 72.8             | 502   | Volume @ inclusion       | 37                    |
| A-4             | 0.2504        | 2932      | 59.5             | 411   | Volume @ inclusion       | 23                    |
| A-21            | 0.2499        | 3620      | 73.8             | 509   | Surface                  | 23                    |
|                 |               | Average   | 62.0             | 427   |                          |                       |
|                 |               | Std. dev. | 10.7             | 74    |                          |                       |

Notes: Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips.

The inclusion in specimen A1 was examined using x-ray fluorescence and was determined to be stainless steel.

All the inclusions in this sample have a similar appearance but vary in size.

Specimens A-16, A-1, and A-9 failed in the upper transition region. Specimen A-14 failed in the lower transition region.

Table A-2.7. Tensile test results; Kyocera SN235P (SN5P); 20 April 2004.

| Specimen Number | Diameter (in) | Load (lb) | Tensile Strength |       | Fracture Origin | Relative Humidity (%) |
|-----------------|---------------|-----------|------------------|-------|-----------------|-----------------------|
|                 |               |           | (ksi)            | (MPa) |                 |                       |
| 16              | 0.2500        | 3837      | 78.2             | 539   | Surface         | 20                    |
| 14              | 0.2500        | 3481      | 70.9             | 489   | Volume          | 20                    |
| 9               | 0.2499        | 4056      | 82.7             | 570   | Surface         | 20                    |
| 11              | 0.2500        | 4101      | 83.5             | 576   | See note        | 22                    |
| 15              | 0.2499        | 4254      | 86.7             | 598   | Surface         | 22                    |
| 8               | 0.2505        | 3173      | 64.4             | 444   | Volume          | 22                    |
| 2               | 0.2499        | 4294      | 87.5             | 604   | Volume          | 22                    |
| 13              | 0.2497        | 4000      | 81.7             | 563   | Volume          | 24                    |
| 17              | 0.2500        | 4030      | 82.1             | 566   | Surface         | 24                    |
| 20              | 0.2496        | 4253      | 86.9             | 599   | Surface         | 24                    |
| 5               | 0.2496        | 4424      | 90.4             | 623   | Volume          | 24                    |
| 7               | 0.2501        | 4474      | 91.1             | 628   | Surface         | 24                    |
| 3               | 0.2500        | 4581      | 93.3             | 643   | Volume          | 54                    |
| 4               | 0.2501        | 4581      | 93.2             | 643   | Surface         | 54                    |
| 10              | 0.2498        | 4071      | 83.1             | 573   | Volume          | 54                    |
| 19              | 0.2500        | 4524      | 92.2             | 635   | Volume          | 54                    |
| 18              | 0.2500        | 4442      | 90.5             | 624   | See note        | 54                    |
| 6               | 0.2499        | 4211      | 85.9             | 592   | Volume          | 54                    |
| 1               | 0.2501        | 4447      | 90.5             | 624   | Surface         | 54                    |
| 12              | 0.2501        | 4242      | 86.3             | 595   | Surface         | 29                    |
|                 |               | Average   | 85.1             | 586   |                 |                       |
|                 |               | Std. dev. | 7.4              | 51    |                 |                       |

Notes: Test temperature: 70 °F (21 °C).

Stressing rate: 150 MPa/s.

Atmosphere: air.

Relative humidity: as noted.

Test fixture: Instron super grips.

Specimens 16, 11, 18, and 12 had multiple failures. A positive identification of the fracture was difficult.

Specimens 16 and 12 appear to be surface failures. Specimens 16 and 11 had both apparent volume and surface failures.

The volume failures of specimens 14, 10, and 6 appear to be at low density areas.



### A-3. Room Temperature Strength Data From Sectored Flexure Specimens

Table A-3.1. Contoured flexural strength results; CoorsTek AD 995 (ALOX); 22 November 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| AB-5-5          | 1.299               | 45           | 0.1582      | 129.0     | 36.7              | 253   |
| AB-4-4          | 1.299               | 45           | 0.1582      | 130.2     | 37.1              | 256   |
| AB-3-2          | 1.299               | 45           | 0.1582      | 138.5     | 39.4              | 272   |
| AB-3-1          | 1.299               | 45           | 0.1580      | 137.2     | 39.2              | 270   |
| AB-4-1          | 1.299               | 45           | 0.1583      | 139.8     | 39.7              | 274   |
| AB-6-4          | 1.299               | 45           | 0.1583      | 143.4     | 40.8              | 281   |
| AB-5-2          | 1.299               | 45           | 0.1580      | 130.8     | 37.3              | 257   |
| AB-3-5          | 1.299               | 45           | 0.1587      | 140.3     | 39.7              | 273   |
| AB-4-5          | 1.299               | 45           | 0.1583      | 136.1     | 38.7              | 267   |
| AB-6-1          | 1.299               | 45           | 0.1588      | 135.8     | 38.3              | 264   |
| AB-3-3          | 1.299               | 45           | 0.1583      | 140.9     | 40.1              | 276   |
| AB-4-3          | 1.299               | 45           | 0.1586      | 135.9     | 38.5              | 265   |
| AB-3-4          | 1.299               | 45           | 0.1588      | 142.4     | 40.2              | 277   |
| AB-6-2          | 1.299               | 45           | 0.1570      | 123.8     | 35.8              | 247   |
| AB-4-2          | 1.299               | 45           | 0.1586      | 133.4     | 37.8              | 260   |
| AB-6-3          | 1.299               | 45           | 0.1587      | 135.9     | 38.4              | 265   |
| AB-6-5          | 1.299               | 45           | 0.1589      | 142.1     | 40.1              | 276   |
| AB-53           | 1.299               | 45           | 0.1582      | 133.7     | 38.1              | 262   |
| AB-5-1          | 1.299               | 45           | 0.1580      | 128.6     | 36.7              | 253   |
| AB-5-4          | 1.299               | 45           | 0.1585      | 127.5     | 36.1              | 249   |
|                 |                     |              |             | Average   | 38.4              | 265   |
|                 |                     |              |             | Std. dev. | 1.5               | 10    |

Notes: Test temperature: 70 °F (21 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Relative humidity: 19%–38%.

Test fixture: SiC2.

Table A-3.2. Contoured flexural strength results; CoorsTek Ce-TZP (ZRO2); 15 November 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| ZB-3-4          | 1.299               | 45           | 0.1577      | 309.5     | 88.7              | 612   |
| ZB-6-5          | 1.299               | 45           | 0.1577      | 307.1     | 88.0              | 607   |
| ZB-3-1          | 1.299               | 45           | 0.1578      | 297.3     | 85.1              | 587   |
| ZB-4-3          | 1.299               | 45           | 0.1577      | 283.7     | 81.3              | 561   |
| ZB-5-5          | 1.299               | 45           | 0.1585      | 282.3     | 80.0              | 552   |
| ZB-4-2          | 1.299               | 45           | 0.1581      | 303.9     | 86.6              | 597   |
| ZB-5-4          | 1.299               | 45           | 0.1579      | 301.3     | 86.1              | 594   |
| ZB-4-1          | 1.299               | 45           | 0.1577      | 298.1     | 85.4              | 589   |
| ZB-5-2          | 1.299               | 45           | 0.1587      | 285.7     | 80.8              | 557   |
| ZB-6-2          | 1.299               | 45           | 0.1577      | 266.6     | 76.4              | 527   |
| ZB-4-4          | 1.299               | 45           | 0.1579      | 321.8     | 92.0              | 634   |
| ZB-3-2          | 1.299               | 45           | 0.1573      | 290.0     | 83.6              | 576   |
| ZB-4-5          | 1.299               | 45           | 0.1580      | 288.1     | 82.2              | 567   |
| ZB-6-1          | 1.299               | 45           | 0.1579      | 277.3     | 79.3              | 547   |
| ZB-3-3          | 1.299               | 45           | 0.1580      | 294.7     | 84.1              | 580   |
| ZB-3-5          | 1.299               | 45           | 0.1578      | 280.2     | 80.2              | 553   |
| ZB-5-3          | 1.299               | 45           | 0.1583      | 304.3     | 86.5              | 596   |
| ZB-6-4          | 1.299               | 45           | 0.1548      | 261.5     | 78.1              | 538   |
| ZB-5-1          | 1.299               | 45           | 0.1578      | 308.1     | 88.2              | 608   |
| ZB-6-3          | 1.299               | 45           | 0.1580      | 294.8     | 84.1              | 580   |
|                 |                     |              |             | Average   | 83.8              | 578   |
|                 |                     |              |             | Std. dev. | 4.0               | 28    |

Notes: Test temperature: 70 °F (21 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Relative humidity: 19%–26%.

Test fixture: see notes.

The fixture failed during the testing of specimen ZB-6-3 at a load of 115.4 lb. The specimen was retested in a fixture SiC1.

At the conclusion of testing specimen ZB-4-2 the top half of the fixture was broken. It is not known if the fixture or specimen failed first.

Specimens ZB-5-4 through ZB-6-3 were tested using the bottom of fixture SiC1 with an new inconel top.

Table A-3.3. Contoured flexural strength results; carborundum enhanced hexoloy SA (SCEH);  
22 November 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| EB-3-4          | 1.299               | 45           | 0.1591      | 101.0     | 28.4              | 196   |
| EB-2-5          | 1.299               | 45           | 0.1581      | 86.0      | 24.5              | 169   |
| EB-4-4          | 1.299               | 45           | 0.1585      | 98.4      | 27.9              | 192   |
| EB-3-2          | 1.299               | 45           | 0.1585      | 130.6     | 37.0              | 255   |
| EB-1-3          | 1.299               | 45           | 0.1572      | 86.5      | 25.0              | 172   |
| EB-4-1          | 1.299               | 45           | 0.1587      | 94.3      | 26.7              | 184   |
| EB-1-2          | 1.299               | 45           | 0.1577      | 81.3      | 23.3              | 161   |
| EB-3-3          | 1.299               | 45           | 0.1586      | 142.3     | 40.3              | 278   |
| EB-1-4          | 1.299               | 45           | 0.1577      | 90.6      | 26.0              | 179   |
| EB-4-3          | 1.299               | 45           | 0.1585      | 97.4      | 27.6              | 190   |
| EB-1-1          | 1.299               | 45           | 0.1576      | 78.7      | 22.6              | 156   |
| EB-4-2          | 1.299               | 45           | 0.1583      | 92.0      | 26.2              | 180   |
| EB-3-5          | 1.299               | 45           | 0.1583      | 116.6     | 33.1              | 229   |
| EB-2-4          | 1.299               | 45           | 0.1584      | 92.9      | 26.4              | 182   |
| EB-3-1          | 1.299               | 45           | 0.1566      | 122.3     | 35.6              | 245   |
| EB-4-5          | 1.299               | 45           | 0.1573      | 92.1      | 26.5              | 183   |
| EB-1-5          | 1.299               | 45           | 0.1590      | 88.9      | 25.0              | 173   |
| EB-2-3          | 1.299               | 45           | 0.1568      | 82.8      | 24.0              | 166   |
| EB-2-1          | 1.299               | 45           | 0.1571      | 93.4      | 27.0              | 186   |
| EB-2-2          | 1.299               | 45           | 0.1559      | 80.8      | 23.8              | 164   |
|                 |                     |              |             | Average   | 27.8              | 192   |
|                 |                     |              |             | Std. dev. | 4.8               | 33    |

Notes: Test temperature: 70 °F (21 °C).  
Crosshead speed: 0.04 in/min.  
Atmosphere: air.  
Relative humidity: 27%.  
Test fixture: SiC1.

Table A-3.4. Contoured flexural strength results; carborundum liquid phase sintered hexoloy SA (SCLH);  
22 November 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| LB-3-2          | 1.299               | 45           | 0.1578      | 166.9     | 47.8              | 329   |
| LB-6-5          | 1.299               | 45           | 0.1583      | 173.0     | 49.2              | 339   |
| LB-5-3          | 1.299               | 45           | 0.1583      | 157.3     | 44.7              | 308   |
| LB-5-1          | 1.299               | 45           | 0.1581      | 139.6     | 39.8              | 274   |
| LB-6-4          | 1.299               | 45           | 0.1595      | 172.3     | 48.2              | 332   |
| LB-4-3          | 1.299               | 45           | 0.1588      | 175.4     | 49.5              | 341   |
| LB-5-5          | 1.299               | 45           | 0.1580      | 147.1     | 42.0              | 290   |
| LB-6-3          | 1.299               | 45           | 0.1589      | 175.6     | 49.5              | 341   |
| LB-3-3          | 1.299               | 45           | 0.1585      | 146.5     | 41.5              | 286   |
| LB-5-2          | 1.299               | 45           | 0.1587      | 141.9     | 40.1              | 277   |
| LB-4-4          | 1.299               | 45           | 0.1583      | 168.2     | 47.8              | 330   |
| LB-3-1          | 1.299               | 45           | 0.1588      | 145.8     | 41.2              | 284   |
| LB-6-2          | 1.299               | 45           | 0.1580      | 158.7     | 45.3              | 312   |
| LB-5-4          | 1.299               | 45           | 0.1575      | 128.1     | 36.8              | 254   |
| LB-5-6          | 1.299               | 45           | 0.1568      | 147.1     | 42.7              | 294   |
| LB-4-1          | 1.299               | 45           | 0.1581      | 166.6     | 47.5              | 327   |
| LB-3-4          | 1.299               | 45           | 0.1587      | 152.1     | 43.0              | 296   |
| LB-6-1          | 1.299               | 45           | 0.1585      | 185.1     | 52.5              | 362   |
| LB-4-5          | 1.299               | 45           | 0.1588      | 158.6     | 44.8              | 309   |
| LB-4-2          | 1.299               | 45           | 0.1585      | 173.5     | 49.2              | 339   |
|                 |                     |              |             | Average   | 45.1              | 311   |
|                 |                     |              |             | Std. dev. | 4.1               | 29    |

Notes: Test temperature: 70 °F (21 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Relative humidity: 26%–27%.

Test fixture: SiC1.

Table A-3.5. Contoured flexural strength results; ceradyne 146-5S (SC46); 15 November 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| SB-3-1          | 1.299               | 45           | 0.1589      | 129.1     | 36.4              | 251   |
| SB-5-5          | 1.299               | 45           | 0.1590      | 134.2     | 37.8              | 260   |
| SB-3-3          | 1.299               | 45           | 0.1595      | 150.0     | 41.9              | 289   |
| SB-6-3          | 1.299               | 45           | 0.1592      | 140.1     | 39.3              | 271   |
| SB-5-3          | 1.299               | 45           | 0.1586      | 143.4     | 40.6              | 280   |
| SB-3-2          | 1.299               | 45           | 0.1589      | 140.6     | 39.6              | 273   |
| SB-4-1          | 1.299               | 45           | 0.1584      | 132.9     | 37.7              | 260   |
| SB-4-3          | 1.299               | 45           | 0.1582      | 139.0     | 39.6              | 273   |
| SB-6-1          | 1.299               | 45           | 0.1594      | 140.1     | 39.2              | 270   |
| SB-4-4          | 1.299               | 45           | 0.1588      | 147.2     | 41.6              | 286   |
| SB-3-5          | 1.299               | 45           | 0.1592      | 143.9     | 40.4              | 279   |
| SB-4-5          | 1.299               | 45           | 0.1592      | 142.8     | 40.1              | 276   |
| SB-5-4          | 1.299               | 45           | 0.1592      | 146.3     | 41.1              | 283   |
| SB-5-2          | 1.299               | 45           | 0.1583      | 143.7     | 40.8              | 282   |
| SB-6-2          | 1.299               | 45           | 0.1586      | 129.9     | 36.8              | 254   |
| SB-5-1          | 1.299               | 45           | 0.1587      | 142.3     | 40.2              | 277   |
| SB-4-6          | 1.299               | 45           | 0.1588      | 141.1     | 39.8              | 275   |
| SB-3-4          | 1.299               | 45           | 0.1599      | 134.2     | 37.3              | 257   |
| SB-4-2          | 1.299               | 45           | 0.1593      | 145.5     | 40.8              | 281   |
| SB-6-4          | 1.299               | 45           | 0.1593      | 130.1     | 36.5              | 251   |
|                 |                     |              |             | Average   | 39.4              | 271   |
|                 |                     |              |             | Std. dev. | 1.7               | 12    |

Notes: Test temperature: 70 °F (21 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Relative humidity: 17%–28%.

Test fixture: SiC3 with contoured load points.

Table A-3.6. Contoured flexural strength results; ceradyne ceralloy 147-31N (SN47).

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| B-4-4           | 1.299               | 45           | 0.1588      | 243.3     | 68.7              | 474   |
| B-4-2           | 1.299               | 45           | 0.1578      | 280.9     | 80.4              | 554   |
| B-4-5           | 1.299               | 45           | 0.1581      | 283.3     | 80.8              | 557   |
| B-4-3           | 1.299               | 45           | 0.1587      | 293.6     | 83.0              | 572   |
| B-6-2           | 1.299               | 45           | 0.1571      | 293.7     | 84.9              | 585   |
| B-4-1           | 1.299               | 45           | 0.1584      | 301.2     | 85.5              | 589   |
| B-5-5           | 1.299               | 45           | 0.1570      | 296.6     | 85.9              | 592   |
| B-6-1           | 1.299               | 45           | 0.1572      | 303.2     | 87.5              | 603   |
| B-3-5           | 1.299               | 45           | 0.1588      | 310.5     | 87.6              | 604   |
| B-5-2           | 1.299               | 45           | 0.1574      | 311.6     | 89.7              | 618   |
| B-5-3           | 1.299               | 45           | 0.1574      | 313.3     | 90.2              | 622   |
| B-5-1           | 1.299               | 45           | 0.1569      | 316.1     | 91.6              | 632   |
| B-5-4           | 1.299               | 45           | 0.1576      | 323.4     | 92.8              | 640   |
| B-3-2           | 1.299               | 45           | 0.1583      | 329.4     | 93.6              | 646   |
| B-3-1           | 1.299               | 45           | 0.1580      | 330.8     | 94.4              | 651   |
| B-6-4           | 1.299               | 45           | 0.1570      | 326.8     | 94.6              | 652   |
| B-6-5           | 1.299               | 45           | 0.1571      | 332.0     | 96.0              | 662   |
| B-6-3           | 1.299               | 45           | 0.1575      | 335.8     | 96.5              | 666   |
| B-3-4           | 1.299               | 45           | 0.1581      | 352.1     | 100.4             | 692   |
| B-3-3           | 1.299               | 45           | 0.1586      | 379.3     | 107.4             | 740   |
|                 |                     |              |             | Average   | 89.6              | 618   |
|                 |                     |              |             | Std. dev. | 8.3               | 57    |

Notes: Test temperature: 70 °F (21 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Relative humidity: 19%–29%.

Specimens B-4-4 and B-4-5 failed at tool marks identified during pretest inspection.

Table A-3.7. Contoured flexural strength results; Kennametal TK-4 (STK4); 11 February 2003.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| B-8-5           | 1.299               | 45           | 0.1574      | 282.8     | 81.4              | 561   |
| B-9-4           | 1.299               | 45           | 0.1576      | 331.0     | 95.0              | 655   |
| B-6-2           | 1.299               | 45           | 0.1581      | 305.8     | 87.2              | 601   |
| B-9-3           | 1.299               | 45           | 0.1575      | 362.8     | 104.3             | 719   |
| B-9-5           | 1.299               | 45           | 0.1580      | 365.6     | 104.4             | 720   |
| B-6-3           | 1.299               | 45           | 0.1582      | 356.8     | 101.6             | 700   |
| B-10-2          | 1.299               | 45           | 0.1571      | 317.1     | 91.7              | 632   |
| B-6-1           | 1.299               | 45           | 0.1579      | 360.9     | 103.2             | 711   |
| B-8-4           | 1.299               | 45           | 0.1583      | 357.1     | 101.5             | 700   |
| B-10-5          | 1.299               | 45           | 0.1577      | 329.0     | 94.3              | 650   |
| B-9-1           | 1.299               | 45           | 0.1579      | 307.2     | 87.8              | 605   |
| B-6-5           | 1.299               | 45           | 0.1585      | 297.4     | 84.3              | 581   |
| B-8-2           | 1.299               | 45           | 0.1581      | 323.8     | 92.3              | 636   |
| B-9-2           | 1.299               | 45           | 0.1575      | 341.8     | 98.2              | 677   |
| B-6-4           | 1.299               | 45           | 0.1581      | 376.8     | 107.4             | 741   |
| B-10-4          | 1.299               | 45           | 0.1575      | 334.3     | 96.1              | 663   |
| B-8-3           | 1.299               | 45           | 0.1578      | 376.8     | 107.9             | 744   |
| B-10-1          | 1.299               | 45           | 0.1578      | 327.7     | 93.8              | 647   |
| B-8-1           | 1.299               | 45           | 0.1575      | 314.2     | 90.3              | 623   |
| B-10-3          | 1.299               | 45           | 0.1576      | 244.5     | 70.2              | 484   |
|                 |                     |              |             | Average   | 94.6              | 653   |
|                 |                     |              |             | Std. dev. | 9.5               | 66    |

Notes: Test temperature: 70 °F (21 °C).  
Crosshead speed: 0.04 in/min.  
Atmosphere: air.  
Relative humidity: 19%–26%.  
Test fixture: SiC/Inc 1.

Table A-3.8. Contoured flexural strength results; Kyocera SN235P (SN5P); 2 February 2004.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| SN5P-B-3-5      | 1.299               | 45           | 0.1576      | 241.0     | 69.2              | 477   |
| SN5P-B-3-2      | 1.299               | 45           | 0.1580      | 268.7     | 76.7              | 529   |
| SN5P-B-3-4      | 1.299               | 45           | 0.1573      | 245.3     | 70.7              | 488   |
| SN5P-B-3-3      | 1.299               | 45           | 0.1580      | 285.2     | 81.4              | 561   |
| SN5P-B-3-1      | 1.299               | 45           | 0.1582      | 284.6     | 81.0              | 559   |
| SN5P-B-4-3      | 1.299               | 45           | 0.1578      | 314.1     | 89.9              | 620   |
| SN5P-B-4-4      | 1.299               | 45           | 0.1583      | 267.2     | 76.0              | 524   |
| SN5P-B-4-1      | 1.299               | 45           | 0.1577      | 286.2     | 82.0              | 566   |
| SN5P-B-4-5      | 1.299               | 45           | 0.1581      | 251.5     | 71.7              | 494   |
| SN5P-B-4-2      | 1.299               | 45           | 0.1578      | 290.3     | 83.1              | 573   |
| SN5P-B-5-5      | 1.299               | 45           | 0.1571      | 324.5     | 93.8              | 647   |
| SN5P-B-5-3      | 1.299               | 45           | 0.1583      | 278.6     | 79.2              | 546   |
| SN5P-B-5-4      | 1.299               | 45           | 0.1577      | 266.9     | 76.5              | 527   |
| SN5P-B-5-1      | 1.299               | 45           | 0.1578      | 259.8     | 74.4              | 513   |
| SN5P-B-5-2      | 1.299               | 45           | 0.1580      | 311.5     | 88.9              | 613   |
| SN5P-B-6-2      | 1.299               | 45           | 0.1578      | 274.4     | 78.5              | 542   |
| SN5P-B-6-1      | 1.299               | 45           | 0.1576      | 305.3     | 87.6              | 604   |
| SN5P-B-6-4      | 1.299               | 45           | 0.1579      | 284.7     | 81.4              | 561   |
| SN5P-B-6-3      | 1.299               | 45           | 0.1579      | 342.4     | 97.9              | 675   |
| SN5P-B-6-5      | 1.299               | 45           | 0.1583      | 326.2     | 92.7              | 639   |
|                 |                     |              |             | Average   | 81.6              | 563   |
|                 |                     |              |             | Std. dev. | 8.0               | 55    |

Notes: Test temperature: 70 °F (21 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Relative humidity: 8%.

Test fixture: SiC/Inc 1.



#### A-4. Elevated Temperature (700 °C) Strength Data From Sector Flexure Specimens

Table A-4.1. Contoured flexural strength results; CoorsTek AD 995; 13 December 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| AB-3-5-8        | 1.299               | 45           | 0.1580      | 132.4     | 37.8              | 261   |
| AB-3-3-7        | 1.299               | 45           | 0.1569      | 116.6     | 33.8              | 233   |
| AB-3-4-7        | 1.299               | 45           | 0.1584      | 108.9     | 30.9              | 213   |
| AB-3-5-7        | 1.299               | 45           | 0.1580      | 127.0     | 36.3              | 250   |
| AB-3-6-8        | 1.299               | 45           | 0.1585      | 129.9     | 36.8              | 254   |
| AB-3-4-6        | 1.299               | 45           | 0.1586      | 114.1     | 32.3              | 223   |
| AB-3-6-7        | 1.299               | 45           | 0.1590      | 120.7     | 34.0              | 234   |
| AB-3-3-6        | 1.299               | 45           | 0.1582      | 125.6     | 35.8              | 247   |
| AB-3-6-6        | 1.299               | 45           | 0.1587      | 129.1     | 36.5              | 252   |
|                 |                     |              |             | Average   | 34.9              | 241   |
|                 |                     |              |             | Std. dev. | 2.3               | 16    |

Notes: Test temperature: 1292 °F (700 °C).  
 Crosshead speed: 0.04 in/min.  
 Atmosphere: air.  
 Heating rate: 10 °C/min.  
 Test fixture: SiC1.  
 Specimen AB-5-6 was broken during heating.

Table A-4.2. Contoured flexural strength results; CoorsTek Ce-TZP (ZRO2); 2 December 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| ZB-6-6          | 1.299               | 45           | 0.1573      | 69.4      | 20.0              | 138   |
| ZB-3-7          | 1.299               | 45           | 0.1577      | 59.3      | 17.0              | 117   |
| ZB-6-7          | 1.299               | 45           | 0.1581      | 37.1      | 10.6              | 73    |
| ZB-4-7          | 1.299               | 45           | 0.1575      | 57.2      | 16.4              | 113   |
| ZB-4-6          | 1.299               | 45           | 0.1580      | 56.2      | 16.0              | 111   |
| ZB-5-7          | 1.299               | 45           | 0.1580      | 67.9      | 19.4              | 134   |
| ZB-3-8          | 1.299               | 45           | 0.1580      | 64.0      | 18.3              | 126   |
| ZB-4-8          | 1.299               | 45           | 0.1580      | 63.1      | 18.0              | 124   |
| ZB-3-6          | 1.299               | 45           | 0.1579      | 58.6      | 16.7              | 115   |
| ZB-5-6          | 1.299               | 45           | 0.1583      | 71.2      | 20.2              | 139   |
|                 |                     |              |             | Average   | 17.3              | 119   |
|                 |                     |              |             | Std. dev. | 2.8               | 19    |

Notes: Test temperature: 1292 °F (700 °C).  
 Crosshead speed: 0.04 in/min.  
 Atmosphere: air.  
 Heating rate: 10 °C/min.  
 Soak time: 10 min.  
 Test fixture: SiC/Inc 1.

Table A-4.3. Contoured flexural strength results; carborundum enhanced hexoloy SA (SCEH); 8 January 2003.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| EB-4-7          | 1.299               | 45           | 0.1582      | 117.7     | 33.5              | 231   |
| EB-3-6          | 1.299               | 45           | 0.1553      | 165.3     | 49.0              | 338   |
| EB-1-7          | 1.299               | 45           | 0.1589      | 110.0     | 31.0              | 214   |
| EB-3-8          | 1.299               | 45           | 0.1585      | 130.5     | 37.0              | 255   |
| EB-2-6          | 1.299               | 45           | 0.1575      | 107.9     | 31.0              | 214   |
| EB-2-8          | 1.299               | 45           | 0.1583      | 107.0     | 30.4              | 210   |
| EB-3-7          | 1.299               | 45           | 0.1589      | 165.5     | 46.7              | 322   |
| EB-1-6          | 1.299               | 45           | 0.1571      | 99.7      | 28.8              | 199   |
| EB-2-7          | 1.299               | 45           | 0.1564      | 90.2      | 26.3              | 182   |
| EB-4-6          | 1.299               | 45           | 0.1581      | 121.4     | 34.6              | 239   |
|                 |                     |              |             | Average   | 34.8              | 240   |
|                 |                     |              |             | Std. dev. | 7.5               | 52    |

Notes: Test temperature: 1292 °F (700 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Heating rate: 10 °C/min.

Test fixture: SiC3.

There was no Grafoil used between the specimen EB-2-6 and the contoured load points.

Table A-4.4. Contoured flexural strength results; carborundum liquid phase sintered hexoloy SA (SCLH); 20 December 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| LB-4-7          | 1.299               | 45           | 0.1593      | 163.3     | 45.8              | 316   |
| LB-3-5          | 1.299               | 45           | 0.1587      | 157.3     | 44.5              | 307   |
| LB-6-8          | 1.299               | 45           | 0.1589      | 154.6     | 43.6              | 300   |
| LB-4-8          | 1.299               | 45           | 0.1575      | 148.5     | 42.7              | 294   |
| LB-4-6          | 1.299               | 45           | 0.1577      | 173.8     | 49.8              | 343   |
| LB-3-6          | 1.299               | 45           | 0.1590      | 118.0     | 33.2              | 229   |
| LB-6-7          | 1.299               | 45           | 0.1587      | 149.1     | 42.1              | 291   |
| LB-6-6          | 1.299               | 45           | 0.1588      | 173.3     | 48.9              | 337   |
| LB-5-7          | 1.299               | 45           | 0.1583      | 148.5     | 42.2              | 291   |
| LB-5-8          | 1.299               | 45           | 0.1560      | 148.5     | 43.6              | 301   |
|                 |                     |              |             | Average   | 43.6              | 301   |
|                 |                     |              |             | Std. dev. | 4.5               | 31    |

Notes: Test temperature: 1292 °F (700 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Heating rate: 10 °C/min.

Soak time: 10 min.

Test fixture: SiC3.

Table A-4.5. Contoured flexural strength results; ceradyne ceralloy 146-5S (SC46); 6 December 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| SB-6-6          | 1.299               | 45           | 0.1587      | 147.3     | 41.6              | 287   |
| SB-3-8          | 1.299               | 45           | 0.1589      | 147.4     | 41.6              | 286   |
| SB-4-7          | 1.299               | 45           | 0.1585      | 140.8     | 39.9              | 275   |
| SB-3-6          | 1.299               | 45           | 0.1590      | 157.2     | 44.3              | 305   |
| SB-3-7          | 1.299               | 45           | 0.1600      | 158.9     | 44.1              | 304   |
| SB-4-8          | 1.299               | 45           | 0.1592      | 127.3     | 35.7              | 246   |
| SB-5-7          | 1.299               | 45           | 0.1590      | 153.9     | 43.3              | 299   |
| SB-5-6          | 1.299               | 45           | 0.1588      | 149.3     | 42.1              | 291   |
| SB-6-5          | 1.299               | 45           | 0.1588      | 140.3     | 39.6              | 273   |
| SB-5-8          | 1.299               | 45           | 0.1588      | 138.8     | 39.2              | 270   |
|                 |                     |              |             | Average   | 41.1              | 284   |
|                 |                     |              |             | Std. dev. | 2.6               | 18    |

Notes: Test temperature: 1292 °F (700 °C).  
 Crosshead speed: 0.04 in/min.  
 Atmosphere: air.  
 Heating rate: 10 °C/min.  
 Soak time: 10 min.  
 Test fixture: SiC/Inc 1.

Table A-4.6. Contoured flexural strength results; ceradyne ceralloy 147-31N (SN47); 22 November 2002.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| 47-B-3-7        | 1.299               | 45           | 0.1582      | 300.9     | 85.6              | 591   |
| 47-B-4-7        | 1.299               | 45           | 0.1576      | 279.7     | 80.3              | 554   |
| 47-B-6-7        | 1.299               | 45           | 0.1573      | 301.8     | 87.0              | 600   |
| 47-B-4-6        | 1.299               | 45           | 0.1587      | 278.9     | 78.8              | 544   |
| 47-B-5-6        | 1.299               | 45           | 0.1577      | 255.4     | 73.2              | 505   |
| 47-B-6-8        | 1.299               | 45           | 0.1583      | 297.0     | 84.4              | 582   |
| 47-B-6-6        | 1.299               | 45           | 0.1576      | 248.1     | 71.2              | 491   |
| 47-B-3-6        | 1.299               | 45           | 0.1586      | 289.2     | 81.9              | 564   |
| 47-B-5-8        | 1.299               | 45           | 0.1573      | 264.5     | 76.2              | 526   |
| 47-B-5-7        | 1.299               | 45           | 0.1569      | 254.1     | 73.7              | 508   |
|                 |                     |              |             | Average   | 79.2              | 546   |
|                 |                     |              |             | Std. dev. | 5.5               | 38    |

Notes: Test temperature: 1292 °F (700 °C).  
 Crosshead speed: 0.04 in/min.  
 Atmosphere: air.  
 Heating rate: 10 °C/min.  
 Test fixture: SiC/Inc 1.

Table A-4.7. Contoured flexural strength results; kennametal TK-4 (STK4); 4 March 2003.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| B-6-7           | 1.299               | 45           | 0.1578      | 370.9     | 106.2             | 732   |
| B-6-6           | 1.299               | 45           | 0.1575      | 368.9     | 106.0             | 731   |
| B-9-6           | 1.299               | 45           | 0.1576      | 357.2     | 102.5             | 707   |
| B-8-6           | 1.299               | 45           | 0.1578      | 341.9     | 97.9              | 675   |
| B-9-7           | 1.299               | 45           | 0.1577      | 372.6     | 106.8             | 736   |
| B-6-8           | 1.299               | 45           | 0.1574      | 324.2     | 93.3              | 643   |
| B-9-8           | 1.299               | 45           | 0.1580      | 352.7     | 100.7             | 694   |
| B-8-7           | 1.299               | 45           | 0.1567      | 326.8     | 95.0              | 655   |
| B-10-6          | 1.299               | 45           | 0.1580      | 346.6     | 98.9              | 682   |
| B-10-7          | 1.299               | 45           | 0.1577      | 333.1     | 95.5              | 658   |
|                 |                     |              |             | Average   | 100.3             | 691   |
|                 |                     |              |             | Std. dev. | 5.0               | 34    |

Notes: Test temperature: 1292 °F (700 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Heating rate: 10 °C/min.

Test fixture: SiC/Inc 1.

Table A-4.8. Contoured flexural strength results; Kyocera SN235P (SN5P); 2 February 2004.

| Specimen Number | Outer Diameter (in) | $\theta$ (°) | Height (in) | Load (lb) | Flexural Strength |       |
|-----------------|---------------------|--------------|-------------|-----------|-------------------|-------|
|                 |                     |              |             |           | (ksi)             | (MPa) |
| SN5P-B-4-7      | 1.299               | 45           | 0.1583      | 272.3     | 77.4              | 534   |
| SN5P-B-3-7      | 1.299               | 45           | 0.1580      | 254.4     | 72.6              | 501   |
| SN5P-B-6-7      | 1.299               | 45           | 0.1581      | 268.0     | 76.4              | 527   |
| SN5P-B-4-6      | 1.299               | 45           | 0.1583      | 254.2     | 72.3              | 498   |
| SN5P-B-6-6      | 1.299               | 45           | 0.1581      | 273.6     | 78.0              | 538   |
| SN5P-B-3-6      | 1.299               | 45           | 0.1571      | 245.5     | 71.0              | 489   |
| SN5P-B-4-8      | 1.299               | 45           | 0.1576      | 249.7     | 71.7              | 494   |
| SN5P-B-5-8      | 1.299               | 45           | 0.1579      | 299.9     | 85.7              | 591   |
| SN5P-B-5-7      | 1.299               | 45           | 0.1575      | 291.5     | 83.8              | 578   |
| SN5P-B-5-6      | 1.299               | 45           | 0.1576      | 266.5     | 76.5              | 527   |
|                 |                     |              |             | Average   | 76.5              | 528   |
|                 |                     |              |             | Std. dev. | 5.0               | 35    |

Notes: Test temperature: 1292 °F (700 °C).

Crosshead speed: 0.04 in/min.

Atmosphere: air.

Heating rate: 10 °C/min.

Test fixture: SiC/Inc 1.

## A-5. Chevron Notch Fracture Toughness Data

Table A-5.1. ALOX.

| Material | B<br>(mm) | W<br>(mm) | a <sub>0</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 3.014     | 4.002     | 1.425                  | 0.5476          | 0.4074          | 3.91                            | 11.50           | 3.92                                       |
| 2        | 3.005     | 4.000     | 1.410                  | 0.5863          | 0.4365          | 3.91                            | 11.55           | 3.92                                       |
| 3        | 3.009     | 4.001     | 1.419                  | 1.1494          | 0.8550          | 3.90                            | 12.20           | 4.15                                       |
| 4        | 3.002     | 3.985     | 1.415                  | 1.1483          | 0.8539          | 3.90                            | 11.20           | 3.85                                       |
| 5        | 3.010     | 4.002     | 1.454                  | 1.1577          | 0.8612          | 3.90                            | 11.20           | 3.88                                       |
|          |           |           |                        |                 |                 | 3.91                            | Average         | 3.94                                       |
|          |           |           |                        |                 |                 | 0.00                            | Std. dev.       | 0.12                                       |

Table A-5.2. ZRO2.

| Material | B<br>(mm) | W<br>(mm) | a <sub>0</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 3.013     | 4.004     | 1.396                  | 1.8269          | 1.5296          | 6.14                            | 15.60           | 5.22                                       |
| 2        | 3.015     | 4.009     | 1.395                  | 1.8333          | 1.5352          | 6.15                            | 17.90           | 5.97                                       |
| 3        | 3.014     | 4.006     | 1.380                  | 1.8288          | 1.5317          | 6.16                            | 18.45           | 6.11                                       |
| 4        | 3.021     | 4.003     | 1.413                  | 1.8310          | 1.5332          | 6.15                            | 16.40           | 5.53                                       |
| 5        | 3.012     | 4.006     | 1.367                  | 1.8329          | 1.5347          | 6.15                            | 17.00           | 5.58                                       |
|          |           |           |                        |                 |                 | 6.15                            | Average         | 5.68                                       |
|          |           |           |                        |                 |                 | 0.00                            | Std. dev.       | 0.36                                       |

Table A-5.3. SCEH.

| Material | B<br>(mm) | W<br>(mm) | a <sub>0</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 2        | 3.015     | 3.999     | 1.485                  | 1.8851          | 1.2865          | 3.15                            | 16.2            | 2.98                                       |
| 3        | 3.015     | 4.006     | 1.486                  | 1.8856          | 1.2930          | 3.18                            | 16.7            | 3.06                                       |
|          |           |           |                        |                 |                 | 3.17                            | Average         | 3.02                                       |
|          |           |           |                        |                 |                 | 0.02                            | Std. dev.       | 0.06                                       |

Note: Specimens 1, 4, and 5 were broken upon arrival from the machinist.

Table A-5.4. SCLH.

| Material | B<br>(mm) | W<br>(mm) | a <sub>0</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 3.011     | 4.008     | 1.466                  | 1.8247          | 1.2258          | 3.05                            | 12.9            | 2.34                                       |
| 2        | 3.017     | 4.011     | 1.469                  | 1.8746          | 1.2792          | 3.15                            | 13.8            | 2.50                                       |
| 3        | 3.019     | 4.013     | 1.463                  | 1.8529          | 1.2531          | 3.09                            | 13.8            | 2.49                                       |
| 4        | 3.025     | 4.007     | 1.465                  | 1.8379          | 1.2402          | 3.07                            | 13.0            | 2.35                                       |
|          |           |           |                        |                 |                 | 3.09                            | Average         | 2.42                                       |
|          |           |           |                        |                 |                 | 0.04                            | Std. dev.       | 0.09                                       |

Note: Specimen 5 was broken upon arrival from the machinist.

Table A-5.5. SC46.

| Material | B<br>(mm) | W<br>(mm) | a <sub>o</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 3.008     | 3.976     | 1.411                  | 0.9026          | 0.6109          | 3.09                            | 14.10           | 4.85                                       |
| 2        | 3.008     | 4.003     | 1.470                  | 0.8996          | 0.6113          | 3.12                            | 13.90           | 4.86                                       |
| 3        | 3.011     | 3.953     | 1.435                  | 0.9214          | 0.6247          | 3.11                            | 14.45           | 5.10                                       |
| 4        | 3.011     | 3.978     | 1.448                  | 0.8958          | 0.6060          | 3.09                            | 14.65           | 5.13                                       |
|          |           |           |                        |                 |                 | 3.10                            | Average         | 4.99                                       |
|          |           |           |                        |                 |                 | 0.01                            | Std. dev.       | 0.15                                       |

Table A-5.6. SN47.

| Material | B<br>(mm) | W<br>(mm) | a <sub>o</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 3.017     | 4.008     | 1.302                  | 0.9729          | 0.6702          | 3.21                            | 20.50           | 6.79                                       |
| 2        | 3.018     | 4.004     | 1.403                  | 0.9506          | 0.6534          | 3.20                            | 19.51           | 6.55                                       |
| 3        | 3.020     | 4.007     | 1.393                  | 0.9651          | 0.6645          | 3.21                            | 19.45           | 6.47                                       |
| 4        | 3.016     | 4.006     | 1.406                  | 0.9346          | 0.6432          | 3.21                            | 12.41           | 4.17                                       |
| 5        | 3.016     | 4.009     | 1.378                  | 0.9391          | 0.6464          | 3.21                            | 19.75           | 6.52                                       |
|          |           |           |                        |                 |                 | 3.21                            | Average         | 6.58                                       |
|          |           |           |                        |                 |                 | 0.01                            | Std. dev.       | 0.14                                       |

Table A-5.7. STK4.

| Material | B<br>(mm) | W<br>(mm) | a <sub>o</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 3.012     | 4.006     | 1.448                  | 2.0161          | 1.4187          | 3.37                            | 42.9            | 7.72                                       |
| 2        | 3.018     | 4.005     | 1.464                  | 2.0149          | 1.4154          | 3.36                            | 41.7            | 7.56                                       |
| 3        | 3.021     | 4.007     | 1.444                  | 2.0161          | 1.4171          | 3.37                            | 41.8            | 7.48                                       |
| 4        | 3.01      | 4.006     | 1.441                  | 2.0162          | 1.4179          | 3.37                            | 42.7            | 7.66                                       |
|          |           |           |                        |                 |                 | 3.37                            | Average         | 7.61                                       |
|          |           |           |                        |                 |                 | 0.01                            | Std. dev.       | 0.11                                       |

Table A-5.8. SN5P.

| Material | B<br>(mm) | W<br>(mm) | a <sub>o</sub><br>(mm) | Dry Mass<br>(g) | Wet Mass<br>(g) | Density<br>(g/cm <sup>3</sup> ) | Max Load<br>(N) | K <sub>IC</sub><br>(MPa*m <sup>1/2</sup> ) |
|----------|-----------|-----------|------------------------|-----------------|-----------------|---------------------------------|-----------------|--|
| 1        | 2.999     | 4.014     | 1.391                  | 1.9358          | 1.3415          | 3.26                            | 48.5            | 8.47                                       |
| 2        | 3.004     | 4.02      | 1.421                  | 1.9558          | 1.3598          | 3.28                            | 48.7            | 8.59                                       |
| 3        | 2.999     | 4.005     | 1.406                  | 1.9332          | 1.3422          | 3.27                            | 50.1            | 8.86                                       |
| 4        | 2.999     | 4.023     | 1.427                  | 1.9441          | 1.3504          | 3.27                            | 48.2            | 8.53                                       |
| 5        | 2.999     | 4.017     | 1.415                  | 1.9403          | 1.3544          | 3.31                            | 50.3            | 8.88                                       |
|          |           |           |                        |                 |                 | 3.28                            | Average         | 8.67                                       |
|          |           |           |                        |                 |                 | 0.02                            | Std. dev.       | 0.19                                       |

# **A-6. Vickers Hardness Data at a 300-g Indentation Load Between Room Temperature and 1000 °C**

Table A-6.1. ALOX.

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 22                    |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 18.3               | 18.0               | 18.2                  | 0.0182                | 1688.8    | 16.6                |
| 2                | 17.4               | 17.4               | 17.4                  | 0.0174                | 1837.5    | 18.0                |
| 3                | 19.8               | 19.0               | 19.4                  | 0.0194                | 1478.2    | 14.5                |
| 4                | 19.5               | 18.3               | 18.9                  | 0.0189                | 1557.4    | 15.3                |
| 5                | 18.6               | 18.6               | 18.6                  | 0.0186                | 1608.0    | 15.8                |
| 6                | 18.8               | 18.8               | 18.8                  | 0.0188                | 1574.0    | 15.4                |
| <b>Average</b>   | 18.7               | 18.4               | 18.5                  | 0.0185                | 1624.0    | 15.9                |
| <b>Std. dev.</b> | 0.9                | 0.6                | 0.7                   | 0.0007                | 125.1     | 1.2                 |
|                  |                    |                    |                       |                       |           |                     |
|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
| <b>Load =</b>    | 300                | 2.9421             |                       | 200                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 20.5               | 21.1               | 20.8                  | 0.0208                | 1285.9    | 12.6                |
| 2                | 22.1               | 21.8               | 22.0                  | 0.0220                | 1154.7    | 11.3                |
| 3                | 20.9               | 20.9               | 20.9                  | 0.0209                | 1273.6    | 12.5                |
| 4                | 19.8               | 19.5               | 19.7                  | 0.0197                | 1440.8    | 14.1                |
| 5                | 19.8               | 19.8               | 19.8                  | 0.0198                | 1419.0    | 13.9                |
| 6                | 20.1               | 19.1               | 19.6                  | 0.0196                | 1448.1    | 14.2                |
| <b>Average</b>   | 20.5               | 20.4               | 20.5                  | 0.0205                | 1337.0    | 13.1                |
| <b>Std. dev.</b> | 0.9                | 1.1                | 0.9                   | 0.0009                | 118.1     | 1.2                 |
|                  |                    |                    |                       |                       |           |                     |
|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
| <b>Load =</b>    | 300                | 2.9421             |                       | 300                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 20.2               | 21.2               | 20.7                  | 0.0207                | 1298.3    | 12.7                |
| 2                | 20.7               | 20.0               | 20.4                  | 0.0204                | 1343.4    | 13.2                |
| 3                | 20.5               | 21.4               | 21.0                  | 0.0210                | 1267.5    | 12.4                |
| 4                | 20.1               | 20.1               | 20.1                  | 0.0201                | 1377.0    | 13.5                |
| 5                | 20.0               | 19.3               | 19.7                  | 0.0197                | 1440.8    | 14.1                |
| 6                | 20.9               | 20.9               | 20.9                  | 0.0209                | 1273.6    | 12.5                |
| <b>Average</b>   | 20.4               | 20.5               | 20.4                  | 0.0204                | 1333.4    | 13.1                |
| <b>Std. dev.</b> | 0.4                | 0.8                | 0.5                   | 0.0005                | 67.3      | 0.7                 |

Table A-6.1. ALOX (continued).

|           | gf                      | N                       |                            | Temp<br>(°C)  |        |             |
|-----------|-------------------------|-------------------------|----------------------------|---------------|--------|-------------|
| Load =    | 300                     | 2.9421                  |                            | 300           |        |             |
| Indent #  | d1<br>( $\mu\text{m}$ ) | d2<br>( $\mu\text{m}$ ) | Ave d<br>( $\mu\text{m}$ ) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 21.3                    | 21.3                    | 21.3                       | 0.0213        | 1226.2 | 12.0        |
| 2         | 22.7                    | 22.7                    | 22.7                       | 0.0227        | 1079.6 | 10.6        |
| 3         | 23.5                    | 23.5                    | 23.5                       | 0.0235        | 1007.4 | 9.9         |
| 4         | 22.7                    | 22.2                    | 22.5                       | 0.0225        | 1103.8 | 10.8        |
| 5         | 22.4                    | 22.4                    | 22.4                       | 0.0224        | 1108.7 | 10.9        |
| 6         | 23.5                    | 23.5                    | 23.5                       | 0.0235        | 1007.4 | 9.9         |
| Average   | 22.7                    | 22.6                    | 22.6                       | 0.0226        | 1088.9 | 10.7        |
| Std. dev. | 0.8                     | 0.8                     | 0.8                        | 0.0008        | 81.1   | 0.8         |
|           |                         |                         |                            |               |        |             |
|           | gf                      | N                       |                            | Temp<br>(°C)  |        |             |
| Load =    | 300                     | 2.9421                  |                            | 500           |        |             |
| Indent #  | d1<br>( $\mu\text{m}$ ) | d2<br>( $\mu\text{m}$ ) | Ave d<br>( $\mu\text{m}$ ) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 25.7                    | 25.1                    | 25.4                       | 0.0254        | 862.3  | 8.5         |
| 2         | 24.1                    | 25.2                    | 24.7                       | 0.0247        | 915.6  | 9.0         |
| 3         | 22.8                    | 22.4                    | 22.6                       | 0.0226        | 1089.2 | 10.7        |
| 4         | 22.8                    | 22.2                    | 22.5                       | 0.0225        | 1098.9 | 10.8        |
| 5         | 23.8                    | 23.8                    | 23.8                       | 0.0238        | 982.1  | 9.6         |
| 6         | 23.6                    | 23.6                    | 23.6                       | 0.0236        | 998.9  | 9.8         |
| Average   | 23.8                    | 23.7                    | 23.8                       | 0.0238        | 991.2  | 9.7         |
| Std. dev. | 1.1                     | 1.3                     | 1.1                        | 0.0011        | 93.5   | 0.9         |
|           |                         |                         |                            |               |        |             |
|           | gf                      | N                       |                            | Temp<br>(°C)  |        |             |
| Load =    | 300                     | 2.9421                  |                            | 600           |        |             |
| Indent #  | d1<br>( $\mu\text{m}$ ) | d2<br>( $\mu\text{m}$ ) | Ave d<br>( $\mu\text{m}$ ) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 29.9                    | 29.0                    | 29.5                       | 0.0295        | 641.4  | 6.3         |
| 2         | 24.5                    | 23.7                    | 24.1                       | 0.0241        | 957.8  | 9.4         |
| 3         | 25.0                    | 23.3                    | 24.2                       | 0.0242        | 953.9  | 9.4         |
| 4         | 27.1                    | 28.8                    | 28.0                       | 0.0280        | 712.1  | 7.0         |
| 5         | 26.6                    | 26.6                    | 26.6                       | 0.0266        | 786.3  | 7.7         |
| 6         | 26.1                    | 25.0                    | 25.6                       | 0.0256        | 852.2  | 8.4         |
| Average   | 26.5                    | 26.1                    | 26.3                       | 0.0263        | 817.3  | 8.0         |
| Std. dev. | 1.9                     | 2.5                     | 2.1                        | 0.0021        | 128.5  | 1.3         |



Table A-6.1. ALOX (continued).

|           | gf                      | N                       |                            | Temp<br>(°C)  |       |             |
|-----------|-------------------------|-------------------------|----------------------------|---------------|-------|-------------|
| Load =    | 300                     | 2.9421                  |                            | 700           |       |             |
| Indent #  | d1<br>( $\mu\text{m}$ ) | d2<br>( $\mu\text{m}$ ) | Ave d<br>( $\mu\text{m}$ ) | Ave d<br>(mm) | HV    | HV<br>(GPa) |
| 1         | 28.2                    | 28.2                    | 28.2                       | 0.0282        | 699.6 | 6.9         |
| 2         | 28.3                    | 27.8                    | 28.1                       | 0.0281        | 707.1 | 6.9         |
| 3         | 27.3                    | 27.3                    | 27.3                       | 0.0273        | 746.4 | 7.3         |
| 4         | 28.7                    | 27.3                    | 28.0                       | 0.0280        | 709.6 | 7.0         |
| 5         | 27.9                    | 27.9                    | 27.9                       | 0.0279        | 714.7 | 7.0         |
| 6         | 27.4                    | 27.4                    | 27.4                       | 0.0274        | 741.0 | 7.3         |
| Average   | 28.0                    | 27.7                    | 27.8                       | 0.0278        | 719.7 | 7.1         |
| Std. dev. | 0.5                     | 0.4                     | 0.4                        | 0.0004        | 19.3  | 0.2         |
|           |                         |                         |                            |               |       |             |
|           | gf                      | N                       |                            | Temp<br>(°C)  |       |             |
| Load =    | 300                     | 2.9421                  |                            | 800           |       |             |
| Indent #  | d1<br>( $\mu\text{m}$ ) | d2<br>( $\mu\text{m}$ ) | Ave d<br>( $\mu\text{m}$ ) | Ave d<br>(mm) | HV    | HV<br>(GPa) |
| 1         | 34.7                    | 34.7                    | 34.7                       | 0.0347        | 462.0 | 4.5         |
| 2         | 31.7                    | 30.9                    | 31.3                       | 0.0313        | 567.9 | 5.6         |
| 3         | 38.1                    | 38.1                    | 38.1                       | 0.0381        | 383.2 | 3.8         |
| 4         | 36.0                    | 34.8                    | 35.4                       | 0.0354        | 443.9 | 4.4         |
| 5         | 35.6                    | 34.1                    | 34.9                       | 0.0349        | 458.1 | 4.5         |
| 6         | 30.0                    | 30.0                    | 30.0                       | 0.0300        | 618.1 | 6.1         |
| Average   | 34.4                    | 33.8                    | 34.1                       | 0.0341        | 488.9 | 4.8         |
| Std. dev. | 3.0                     | 2.9                     | 2.9                        | 0.0029        | 86.9  | 0.9         |

Table A-6.2. ZRO2.

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 25.0       | 25.7       | 25.4          | 0.0254        | 865.7  | 8.5         |
| 2         | 28.6       | 28.2       | 28.4          | 0.0284        | 689.7  | 6.8         |
| 3         | 24.2       | 23.4       | 23.8          | 0.0238        | 982.1  | 9.6         |
| 4         | 23.8       | 23.4       | 23.6          | 0.0236        | 998.9  | 9.8         |
| 5         | 22.3       | 23.2       | 22.8          | 0.0228        | 1074.9 | 10.5        |
| 6         | 28.3       | 28.9       | 28.6          | 0.0286        | 680.1  | 6.7         |
| Average   | 25.4       | 25.5       | 25.4          | 0.0254        | 881.9  | 8.6         |
| Std. dev. | 2.5        | 2.6        | 2.5           | 0.0025        | 166.7  | 1.6         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 200           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 26.2       | 26.3       | 26.3          | 0.0263        | 807.4  | 7.9         |
| 2         | 25.5       | 25.5       | 25.5          | 0.0255        | 855.5  | 8.4         |
| 3         | 26.1       | 26.1       | 26.1          | 0.0261        | 816.7  | 8.0         |
| 4         | 26.4       | 25.7       | 26.1          | 0.0261        | 819.8  | 8.0         |
| 5         | 27.8       | 27.8       | 27.8          | 0.0278        | 719.8  | 7.1         |
| 6         | 25.3       | 25.0       | 25.2          | 0.0252        | 879.5  | 8.6         |
| Average   | 26.2       | 26.1       | 26.1          | 0.0261        | 816.5  | 8.0         |
| Std. dev. | 0.9        | 1.0        | 0.9           | 0.0009        | 54.7   | 0.5         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 300           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 27.6       | 27.3       | 27.5          | 0.0275        | 738.3  | 7.2         |
| 2         | 27.1       | 27.1       | 27.1          | 0.0271        | 757.5  | 7.4         |
| 3         | 28.1       | 28.1       | 28.1          | 0.0281        | 704.6  | 6.9         |
| 4         | 28.1       | 27.6       | 27.9          | 0.0279        | 717.3  | 7.0         |
| 5         | 27.9       | 27.9       | 27.9          | 0.0279        | 714.7  | 7.0         |
| Average   | 27.8       | 27.6       | 27.7          | 0.0277        | 726.5  | 7.1         |
| Std. dev. | 0.4        | 0.4        | 0.4           | 0.0004        | 21.3   | 0.2         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 31.9       | 31.3       | 31.6          | 0.0316        | 557.1  | 5.5         |
| 2         | 31.9       | 31.9       | 31.9          | 0.0319        | 546.7  | 5.4         |
| 3         | 32.1       | 32.1       | 32.1          | 0.0321        | 539.9  | 5.3         |
| 4         | 31.1       | 31.1       | 31.1          | 0.0311        | 575.2  | 5.6         |
| 5         | 31.6       | 31.1       | 31.4          | 0.0314        | 566.0  | 5.6         |
| Average   | 31.7       | 31.5       | 31.6          | 0.0316        | 557.0  | 5.5         |
| Std. dev. | 0.4        | 0.5        | 0.4           | 0.0004        | 14.2   | 0.1         |

Table A-6.2. ZRO2 (continued).

|           | gf         | N          |               | Temp<br>(°C)  |       |             |
|-----------|------------|------------|---------------|---------------|-------|-------------|
| Load =    | 300        | 2.9421     |               | 500           |       |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV    | HV<br>(GPa) |
| 1         | 34.2       | 34.2       | 34.2          | 0.0342        | 475.6 | 4.7         |
| 2         | 33.8       | 33.8       | 33.8          | 0.0338        | 487.0 | 4.8         |
| 3         | 34.1       | 34.1       | 34.1          | 0.0341        | 478.4 | 4.7         |
| 4         | 35.7       | 35.7       | 35.7          | 0.0357        | 436.5 | 4.3         |
| 5         | 34.7       | 33.5       | 34.1          | 0.0341        | 478.4 | 4.7         |
| 6         | 34.3       | 34.3       | 34.3          | 0.0343        | 472.9 | 4.6         |
| Average   | 34.5       | 34.3       | 34.4          | 0.0344        | 471.5 | 4.6         |
| Std. dev. | 0.7        | 0.8        | 0.7           | 0.0007        | 17.8  | 0.2         |
|           | gf         | N          |               | Temp<br>(°C)  |       |             |
| Load =    | 300        | 2.9421     |               | 600           |       |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV    | HV<br>(GPa) |
| 1         | 37.4       | 37.4       | 37.4          | 0.0374        | 397.7 | 3.9         |
| 2         | 36.2       | 36.2       | 36.2          | 0.0362        | 424.5 | 4.2         |
| 3         | 36.5       | 36.9       | 36.7          | 0.0367        | 413.0 | 4.1         |
| 4         | 39.6       | 39.2       | 39.4          | 0.0394        | 358.4 | 3.5         |
| 5         | 36.0       | 37.2       | 36.6          | 0.0366        | 415.3 | 4.1         |
| Average   | 37.1       | 37.4       | 37.3          | 0.0373        | 401.8 | 3.9         |
| Std. dev. | 1.5        | 1.1        | 1.3           | 0.0013        | 26.1  | 0.3         |
|           | gf         | N          |               | Temp<br>(°C)  |       |             |
| Load =    | 300        | 2.9421     |               | 700           |       |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV    | HV<br>(GPa) |
| 1         | 40.0       | 39.7       | 39.9          | 0.0399        | 350.3 | 3.4         |
| 2         | 40.1       | 39.9       | 40.0          | 0.0400        | 347.7 | 3.4         |
| 3         | 38.9       | 38.9       | 38.9          | 0.0389        | 367.6 | 3.6         |
| 4         | 38.0       | 38.9       | 38.5          | 0.0385        | 376.3 | 3.7         |
| 5         | 38.7       | 37.9       | 38.3          | 0.0383        | 379.3 | 3.7         |
| Average   | 39.1       | 39.1       | 39.1          | 0.0391        | 364.2 | 3.6         |
| Std. dev. | 0.9        | 0.8        | 0.8           | 0.0008        | 14.6  | 0.1         |
|           | gf         | N          |               | Temp<br>(°C)  |       |             |
| Load =    | 300        | 2.9421     |               | 800           |       |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV    | HV<br>(GPa) |
| 1         | 46.6       | 48.7       | 47.7          | 0.0477        | 245.0 | 2.4         |
| 2         | 42.0       | 41.0       | 41.5          | 0.0415        | 323.0 | 3.2         |
| 3         | 43.0       | 42.5       | 42.8          | 0.0428        | 304.4 | 3.0         |
| 4         | 42.0       | 41.6       | 41.8          | 0.0418        | 318.4 | 3.1         |
| 5         | 42.4       | 42.2       | 42.3          | 0.0423        | 310.9 | 3.0         |
| 6         | 44.1       | 43.5       | 43.8          | 0.0438        | 290.0 | 2.8         |
| 7         | 41.8       | 41.8       | 41.8          | 0.0418        | 318.4 | 3.1         |
| Average   | 43.1       | 43.0       | 43.1          | 0.0431        | 301.4 | 3.0         |
| Std. dev. | 1.7        | 2.6        | 2.2           | 0.0022        | 27.2  | 0.3         |

Table A-6.3. SCEH.

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 22                    |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 14.5               | 14.1               | 14.3                  | 0.0143                | 2720.5    | 26.7                |
| 2                | 14.1               | 14.2               | 14.2                  | 0.0142                | 2778.5    | 27.2                |
| 3                | 14.3               | 14.1               | 14.2                  | 0.0142                | 2759.0    | 27.1                |
| 4                | 14.2               | 14.0               | 14.1                  | 0.0141                | 2798.2    | 27.4                |
| 5                | 14.1               | 14.4               | 14.3                  | 0.0143                | 2739.6    | 26.9                |
| <b>Average</b>   | 14.2               | 14.2               | 14.2                  | 0.0142                | 2759.2    | 27.1                |
| <b>Std. dev.</b> | 0.2                | 0.2                | 0.1                   | 0.0001                | 30.7      | 0.3                 |

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 200                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 14.7               | 14.8               | 14.8                  | 0.0148                | 2557.1    | 25.1                |
| 2                | 14.9               | 15.1               | 15.0                  | 0.0150                | 2472.5    | 24.2                |
| 3                | 15.4               | 14.6               | 15.0                  | 0.0150                | 2472.5    | 24.2                |
| 4                | 14.6               | 14.6               | 14.6                  | 0.0146                | 2609.9    | 25.6                |
| 5                | 14.8               | 14.7               | 14.8                  | 0.0148                | 2557.1    | 25.1                |
| <b>Average</b>   | 14.9               | 14.8               | 14.8                  | 0.0148                | 2533.8    | 24.8                |
| <b>Std. dev.</b> | 0.3                | 0.2                | 0.2                   | 0.0002                | 59.9      | 0.6                 |

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 400                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 17.3               | 16.6               | 17.0                  | 0.0170                | 1936.4    | 19.0                |
| 2                | 16.8               | 16.6               | 16.7                  | 0.0167                | 1994.8    | 19.6                |
| 3                | 16.9               | 17.0               | 17.0                  | 0.0170                | 1936.4    | 19.0                |
| 4                | 16.9               | 16.9               | 16.9                  | 0.0169                | 1947.8    | 19.1                |
| 5                | 17.0               | 17.1               | 17.1                  | 0.0171                | 1913.7    | 18.8                |
| <b>Average</b>   | 17.0               | 16.8               | 16.9                  | 0.0169                | 1945.8    | 19.1                |
| <b>Std. dev.</b> | 0.2                | 0.2                | 0.1                   | 0.0001                | 30.0      | 0.3                 |

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 600                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 18.4               | 18.7               | 18.6                  | 0.0186                | 1616.7    | 15.9                |
| 2                | 18.6               | 18.9               | 18.8                  | 0.0188                | 1582.4    | 15.5                |
| 3                | 18.8               | 19.2               | 19.0                  | 0.0190                | 1541.1    | 15.1                |
| 4                | 18.7               | 18.8               | 18.8                  | 0.0188                | 1582.4    | 15.5                |
| 5                | 18.7               | 18.9               | 18.8                  | 0.0188                | 1574.0    | 15.4                |
| <b>Average</b>   | 18.6               | 18.9               | 18.8                  | 0.0188                | 1579.3    | 15.5                |
| <b>Std. dev.</b> | 0.2                | 0.2                | 0.2                   | 0.0002                | 27.0      | 0.3                 |

Table A-6.3. SCEH (continued).

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 800                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 22.1               | 22.2               | 22.2                  | 0.0222                | 1133.9    | 11.1                |
| 2                | 21.9               | 21.7               | 21.8                  | 0.0218                | 1170.6    | 11.5                |
| 3                | 21.6               | 21.5               | 21.6                  | 0.0216                | 1197.9    | 11.7                |
| 4                | 21.7               | 21.9               | 21.8                  | 0.0218                | 1170.6    | 11.5                |
| 5                | 22.2               | 22.5               | 22.4                  | 0.0224                | 1113.7    | 10.9                |
| <b>Average</b>   | 21.9               | 22.0               | 21.9                  | 0.0219                | 1157.4    | 11.4                |
| <b>Std. dev.</b> | 0.3                | 0.4                | 0.3                   | 0.0003                | 33.4      | 0.3                 |

Table A-6.4. SCLH.

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 16.4       | 16.1       | 16.3          | 0.0163        | 2106.8 | 20.7        |
| 2         | 16.2       | 16.0       | 16.1          | 0.0161        | 2146.2 | 21.0        |
| 3         | 16.2       | 16.2       | 16.2          | 0.0162        | 2119.8 | 20.8        |
| 4         | 16.0       | 16.1       | 16.1          | 0.0161        | 2159.6 | 21.2        |
| 5         | 16.4       | 16.5       | 16.5          | 0.0165        | 2055.9 | 20.2        |
| Average   | 16.2       | 16.2       | 16.2          | 0.0162        | 2117.6 | 20.8        |
| Std. dev. | 0.2        | 0.2        | 0.2           | 0.0002        | 40.4   | 0.4         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 200           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 18.5       | 17.8       | 18.2          | 0.0182        | 1688.8 | 16.6        |
| 2         | 18.3       | 18.0       | 18.2          | 0.0182        | 1688.8 | 16.6        |
| 3         | 18.1       | 18.4       | 18.3          | 0.0183        | 1670.3 | 16.4        |
| 4         | 18.4       | 18.0       | 18.2          | 0.0182        | 1679.5 | 16.5        |
| 5         | 18.1       | 17.8       | 18.0          | 0.0180        | 1726.6 | 16.9        |
| Average   | 18.3       | 18.0       | 18.1          | 0.0181        | 1690.8 | 16.6        |
| Std. dev. | 0.2        | 0.2        | 0.1           | 0.0001        | 21.4   | 0.2         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 19.1       | 19.5       | 19.3          | 0.0193        | 1493.5 | 14.6        |
| 2         | 19.5       | 20.0       | 19.8          | 0.0198        | 1426.2 | 14.0        |
| 3         | 20.2       | 20.0       | 20.1          | 0.0201        | 1377.0 | 13.5        |
| 4         | 19.7       | 20.0       | 19.9          | 0.0199        | 1411.9 | 13.8        |
| 5         | 19.7       | 19.6       | 19.7          | 0.0197        | 1440.8 | 14.1        |
| Average   | 19.6       | 19.8       | 19.7          | 0.0197        | 1429.9 | 14.0        |
| Std. dev. | 0.4        | 0.2        | 0.3           | 0.0003        | 42.7   | 0.4         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 22.1       | 21.3       | 21.7          | 0.0217        | 1181.4 | 11.6        |
| 2         | 21.1       | 21.3       | 21.2          | 0.0212        | 1237.8 | 12.1        |
| 3         | 21.5       | 21.3       | 21.4          | 0.0214        | 1214.8 | 11.9        |
| 4         | 21.1       | 21.1       | 21.1          | 0.0211        | 1249.6 | 12.3        |
| 5         | 21.4       | 21.4       | 21.4          | 0.0214        | 1214.8 | 11.9        |
| Average   | 21.4       | 21.3       | 21.4          | 0.0214        | 1219.7 | 12.0        |
| Std. dev. | 0.4        | 0.1        | 0.2           | 0.0002        | 26.1   | 0.3         |

Table A-6.4. SCLH (continued).

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 800                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 24.2               | 23.8               | 24.0                  | 0.0240                | 965.8     | 9.5                 |
| 2                | 23.4               | 23.5               | 23.5                  | 0.0235                | 1011.7    | 9.9                 |
| 3                | 23.2               | 23.3               | 23.3                  | 0.0233                | 1029.2    | 10.1                |
| 4                | 23.4               | 23.5               | 23.5                  | 0.0235                | 1011.7    | 9.9                 |
| 5                | 24.1               | 24.2               | 24.2                  | 0.0242                | 953.9     | 9.4                 |
| <b>Average</b>   | 23.7               | 23.7               | 23.7                  | 0.0237                | 994.4     | 9.8                 |
| <b>Std. dev.</b> | 0.5                | 0.4                | 0.4                   | 0.0004                | 32.6      | 0.3                 |

Table A-6.5. SC46.

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 15.2       | 16.7       | 16.0          | 0.0160        | 2186.8 | 21.4        |
| 2         | 14.7       | 14.7       | 14.7          | 0.0147        | 2574.5 | 25.2        |
| 3         | 17.5       | 17.1       | 17.3          | 0.0173        | 1858.8 | 18.2        |
| 4         | 17.4       | 18.2       | 17.8          | 0.0178        | 1755.8 | 17.2        |
| 5         | 15.2       | 16.5       | 15.9          | 0.0159        | 2214.5 | 21.7        |
| 6         | 16.4       | 16.5       | 16.5          | 0.0165        | 2055.9 | 20.2        |
| Average   | 16.1       | 16.6       | 16.3          | 0.0163        | 2107.7 | 20.7        |
| Std. dev. | 1.2        | 1.1        | 1.1           | 0.0011        | 291.2  | 2.9         |

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 200           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 17.4       | 18.0       | 17.7          | 0.0177        | 1775.7 | 17.4        |
| 2         | 16.5       | 16.7       | 16.6          | 0.0166        | 2018.9 | 19.8        |
| 3         | 17.0       | 18.3       | 17.7          | 0.0177        | 1785.8 | 17.5        |
| 4         | 18.1       | 18.1       | 18.1          | 0.0181        | 1698.1 | 16.7        |
| 5         | 16.6       | 17.5       | 17.1          | 0.0171        | 1913.7 | 18.8        |
| 6         | 17.7       | 17.7       | 17.7          | 0.0177        | 1775.7 | 17.4        |
| Average   | 17.2       | 17.7       | 17.5          | 0.0175        | 1828.0 | 17.9        |
| Std. dev. | 0.6        | 0.6        | 0.5           | 0.0005        | 116.5  | 1.1         |

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 300           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 16.4       | 17.1       | 16.8          | 0.0168        | 1982.9 | 19.4        |
| 2         | 17.6       | 16.7       | 17.2          | 0.0172        | 1891.5 | 18.5        |
| 3         | 17.7       | 16.6       | 17.2          | 0.0172        | 1891.5 | 18.5        |
| 4         | 18.8       | 18.2       | 18.5          | 0.0185        | 1625.5 | 15.9        |
| 5         | 17.3       | 16.5       | 16.9          | 0.0169        | 1947.8 | 19.1        |
| 6         | 17.2       | 17.6       | 17.4          | 0.0174        | 1837.5 | 18.0        |
| Average   | 17.5       | 17.1       | 17.3          | 0.0173        | 1862.8 | 18.3        |
| Std. dev. | 0.8        | 0.7        | 0.6           | 0.0006        | 126.7  | 1.2         |



Table A-6.5. SC46 (continued).

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 17.9       | 17.9       | 17.9          | 0.0179        | 1736.3 | 17.0        |
| 2         | 19.0       | 19.0       | 19.0          | 0.0190        | 1541.1 | 15.1        |
| 3         | 17.9       | 17.9       | 17.9          | 0.0179        | 1736.3 | 17.0        |
| 4         | 17.9       | 17.9       | 17.9          | 0.0179        | 1736.3 | 17.0        |
| 5         | 17.2       | 17.2       | 17.2          | 0.0172        | 1880.5 | 18.4        |
| Average   | 18.0       | 18.0       | 18.0          | 0.0180        | 1726.1 | 16.9        |
| Std. dev. | 0.6        | 0.6        | 0.6           | 0.0006        | 120.8  | 1.2         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 500           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 17.9       | 18.3       | 18.1          | 0.0181        | 1698.1 | 16.7        |
| 2         | 18.2       | 20.0       | 19.1          | 0.0191        | 1525.0 | 15.0        |
| 3         | 19.3       | 18.5       | 18.9          | 0.0189        | 1557.4 | 15.3        |
| 4         | 20.5       | 20.5       | 20.5          | 0.0205        | 1323.8 | 13.0        |
| 5         | 18.5       | 18.5       | 18.5          | 0.0185        | 1625.5 | 15.9        |
| 6         | 18.5       | 20.6       | 19.6          | 0.0196        | 1455.6 | 14.3        |
| Average   | 18.8       | 19.4       | 19.1          | 0.0191        | 1530.9 | 15.0        |
| Std. dev. | 0.9        | 1.1        | 0.8           | 0.0008        | 131.3  | 1.3         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 20.2       | 20.2       | 20.2          | 0.0202        | 1363.4 | 13.4        |
| 2         | 20.6       | 21.9       | 21.3          | 0.0213        | 1232.0 | 12.1        |
| 3         | 21.0       | 21.0       | 21.0          | 0.0210        | 1261.5 | 12.4        |
| 4         | 21.3       | 21.5       | 21.4          | 0.0214        | 1214.8 | 11.9        |
| 5         | 22.8       | 23.6       | 23.2          | 0.0232        | 1033.6 | 10.1        |
| 6         | 20.2       | 19.7       | 20.0          | 0.0200        | 1397.8 | 13.7        |
| Average   | 21.0       | 21.3       | 21.2          | 0.0212        | 1250.5 | 12.3        |
| Std. dev. | 1.0        | 1.4        | 1.2           | 0.0012        | 129.0  | 1.3         |

Table A-6.5. SC46 (continued).

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 700                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 23.5               | 23.5               | 23.5                  | 0.0235                | 1007.4    | 9.9                 |
| 2                | 25.9               | 25.2               | 25.6                  | 0.0256                | 852.2     | 8.4                 |
| 3                | 21.7               | 21.2               | 21.5                  | 0.0215                | 1209.1    | 11.9                |
| 4                | 21.4               | 21.4               | 21.4                  | 0.0214                | 1214.8    | 11.9                |
| 5                | 24.4               | 24.4               | 24.4                  | 0.0244                | 934.4     | 9.2                 |
| 6                | 20.7               | 19.8               | 20.3                  | 0.0203                | 1356.7    | 13.3                |
| <b>Average</b>   | 22.9               | 22.6               | 22.8                  | 0.0228                | 1095.8    | 10.7                |
| <b>Std. dev.</b> | 2.0                | 2.1                | 2.0                   | 0.0020                | 194.0     | 1.9                 |
|                  |                    |                    |                       |                       |           |                     |
|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
| <b>Load =</b>    | 300                | 2.9421             |                       | 800                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 23.2               | 23.2               | 23.2                  | 0.0232                | 1033.6    | 10.1                |
| 2                | 23.9               | 23.1               | 23.5                  | 0.0235                | 1007.4    | 9.9                 |
| 3                | 23.6               | 23.6               | 23.6                  | 0.0236                | 998.9     | 9.8                 |
| 4                | 25.4               | 23.1               | 24.3                  | 0.0243                | 946.0     | 9.3                 |
| 5                | 23.1               | 23.1               | 23.1                  | 0.0231                | 1042.6    | 10.2                |
| 6                | 22.9               | 25.2               | 24.1                  | 0.0241                | 961.8     | 9.4                 |
| <b>Average</b>   | 23.7               | 23.6               | 23.6                  | 0.0236                | 998.4     | 9.8                 |
| <b>Std. dev.</b> | 0.9                | 0.8                | 0.5                   | 0.0005                | 38.3      | 0.4                 |

Table A-6.6. SN47; September 2002.

|                  |                    |                    |                       |                       |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
|                  | <b>gf</b>          | <b>N</b>           |                       | <b>Temp<br/>(°C)</b>  |           |                     |
| <b>Load =</b>    | 300                | 2.9421             |                       | 22                    |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 19.0               | 18.5               | 18.8                  | 0.0188                | 1582.4    | 15.5                |
| 2                | 19.7               | 18.8               | 19.3                  | 0.0193                | 1501.3    | 14.7                |
| 3                | 18.8               | 18.5               | 18.7                  | 0.0187                | 1599.4    | 15.7                |
| 4                | 18.6               | 18.2               | 18.4                  | 0.0184                | 1643.2    | 16.1                |
| 5                | 18.4               | 18.4               | 18.4                  | 0.0184                | 1643.2    | 16.1                |
| 6                | 18.6               | 18.2               | 18.4                  | 0.0184                | 1643.2    | 16.1                |
| <b>Average</b>   | 18.9               | 18.4               | 18.6                  | 0.0186                | 1602.1    | 15.7                |
| <b>Std. dev.</b> | 0.5                | 0.2                | 0.3                   | 0.0003                | 55.9      | 0.5                 |
|                  |                    |                    |                       |                       |           |                     |
|                  | <b>gf</b>          | <b>N</b>           |                       | <b>Temp<br/>(°C)</b>  |           |                     |
| <b>Load =</b>    | 300                | 2.9421             |                       | 200                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 20.6               | 20.3               | 20.5                  | 0.0205                | 1330.3    | 13.0                |
| 2                | 20.0               | 20.0               | 20.0                  | 0.0200                | 1390.8    | 13.6                |
| 3                | 20.3               | 19.4               | 19.9                  | 0.0199                | 1411.9    | 13.8                |
| 4                | 19.9               | 19.6               | 19.8                  | 0.0198                | 1426.2    | 14.0                |
| 5                | 20.1               | 19.3               | 19.7                  | 0.0197                | 1433.5    | 14.1                |
| 6                | 19.5               | 19.5               | 19.5                  | 0.0195                | 1463.0    | 14.3                |
| <b>Average</b>   | 20.1               | 19.7               | 19.9                  | 0.0199                | 1409.3    | 13.8                |
| <b>Std. dev.</b> | 0.4                | 0.4                | 0.3                   | 0.0003                | 45.5      | 0.4                 |
|                  |                    |                    |                       |                       |           |                     |
|                  | <b>gf</b>          | <b>N</b>           |                       | <b>Temp<br/>(°C)</b>  |           |                     |
| <b>Load =</b>    | 300                | 2.9421             |                       | 300                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 20.6               | 20.1               | 20.4                  | 0.0204                | 1343.4    | 13.2                |
| 2                | 20.1               | 19.5               | 19.8                  | 0.0198                | 1419.0    | 13.9                |
| 3                | 20.2               | 19.6               | 19.9                  | 0.0199                | 1404.8    | 13.8                |
| 4                | 20.7               | 20.1               | 20.4                  | 0.0204                | 1336.8    | 13.1                |
| 5                | 22.0               | 21.0               | 21.5                  | 0.0215                | 1203.5    | 11.8                |
| 6                | 21.7               | 21.7               | 21.7                  | 0.0217                | 1181.4    | 11.6                |
| <b>Average</b>   | 20.9               | 20.3               | 20.6                  | 0.0206                | 1314.8    | 12.9                |
| <b>Std. dev.</b> | 0.8                | 0.9                | 0.8                   | 0.0008                | 100.4     | 1.0                 |

Table A-6.6. SN47; September 2002 (continued).

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 21.7       | 21.4       | 21.6          | 0.0216        | 1197.9 | 11.7        |
| 2         | 21.8       | 21.6       | 21.7          | 0.0217        | 1181.4 | 11.6        |
| 3         | 21.3       | 20.2       | 20.8          | 0.0208        | 1292.1 | 12.7        |
| 4         | 21.5       | 21.5       | 21.5          | 0.0215        | 1203.5 | 11.8        |
| 5         | 22.1       | 21.5       | 21.8          | 0.0218        | 1170.6 | 11.5        |
| 6         | 22.1       | 21.3       | 21.7          | 0.0217        | 1181.4 | 11.6        |
| Average   | 21.8       | 21.3       | 21.5          | 0.0215        | 1204.5 | 11.8        |
| Std. dev. | 0.3        | 0.5        | 0.4           | 0.0004        | 44.6   | 0.4         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 500           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 22.0       | 21.2       | 21.6          | 0.0216        | 1192.4 | 11.7        |
| 2         | 21.6       | 21.0       | 21.3          | 0.0213        | 1226.2 | 12.0        |
| 3         | 21.0       | 21.0       | 21.0          | 0.0210        | 1261.5 | 12.4        |
| 4         | 21.8       | 20.7       | 21.3          | 0.0213        | 1232.0 | 12.1        |
| 5         | 21.5       | 21.2       | 21.4          | 0.0214        | 1220.5 | 12.0        |
| 6         | 21.8       | 20.8       | 21.3          | 0.0213        | 1226.2 | 12.0        |
| Average   | 21.6       | 21.0       | 21.3          | 0.0213        | 1226.5 | 12.0        |
| Std. dev. | 0.3        | 0.2        | 0.2           | 0.0002        | 22.2   | 0.2         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 21.6       | 21.2       | 21.4          | 0.0214        | 1214.8 | 11.9        |
| 2         | 23.2       | 22.4       | 22.8          | 0.0228        | 1070.2 | 10.5        |
| 3         | 23.4       | 22.2       | 22.8          | 0.0228        | 1070.2 | 10.5        |
| 4         | 23.0       | 22.5       | 22.8          | 0.0228        | 1074.9 | 10.5        |
| 5         | 23.1       | 21.5       | 22.3          | 0.0223        | 1118.7 | 11.0        |
| Average   | 22.9       | 22.0       | 22.4          | 0.0224        | 1109.7 | 10.9        |
| Std. dev. | 0.7        | 0.6        | 0.6           | 0.0006        | 62.2   | 0.6         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 700           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 22.5       | 22.0       | 22.3          | 0.0223        | 1123.7 | 11.0        |
| 2         | 23.7       | 22.1       | 22.9          | 0.0229        | 1060.8 | 10.4        |
| 3         | 22.7       | 21.7       | 22.2          | 0.0222        | 1128.8 | 11.1        |
| 4         | 22.9       | 22.5       | 22.7          | 0.0227        | 1079.6 | 10.6        |
| 5         | 23.7       | 21.9       | 22.8          | 0.0228        | 1070.2 | 10.5        |
| Average   | 23.1       | 22.0       | 22.6          | 0.0226        | 1092.6 | 10.7        |
| Std. dev. | 0.6        | 0.3        | 0.3           | 0.0003        | 31.5   | 0.3         |

Table A-6.6. SN47; September 2002 (continued).

|                  | <b>gf</b>          | <b>N</b>           |                       | <b>Temp<br/>(°C)</b>  |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 800                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 23.0               | 23.0               | 23.0                  | 0.0230                | 1051.6    | 10.3                |
| 2                | 22.8               | 22.8               | 22.8                  | 0.0228                | 1070.2    | 10.5                |
| 3                | 23.0               | 23.0               | 23.0                  | 0.0230                | 1051.6    | 10.3                |
| 4                | 22.4               | 21.9               | 22.2                  | 0.0222                | 1133.9    | 11.1                |
| 5                | 23.0               | 22.5               | 22.8                  | 0.0228                | 1074.9    | 10.5                |
| <b>Average</b>   | 22.8               | 22.6               | 22.7                  | 0.0227                | 1076.5    | 10.6                |
| <b>Std. dev.</b> | 0.3                | 0.5                | 0.3                   | 0.0003                | 33.8      | 0.3                 |

Table A-6.7. SN47; February 2004.

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 22                    | Leco      |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 19.4               | 19.1               | 19.3                  | 0.0193                | 1501.3    | 14.7                |
| 2                | 18.8               | 19.1               | 19.0                  | 0.0190                | 1549.2    | 15.2                |
| 3                | 19.2               | 19.4               | 19.3                  | 0.0193                | 1493.5    | 14.6                |
| 4                | 19.2               | 19.0               | 19.1                  | 0.0191                | 1525.0    | 15.0                |
| 5                | 19.1               | 19.1               | 19.1                  | 0.0191                | 1525.0    | 15.0                |
| <b>Average</b>   | 19.1               | 19.1               | 19.1                  | 0.0191                | 1518.8    | 14.9                |
| <b>Std. dev.</b> | 0.2                | 0.2                | 0.1                   | 0.0001                | 22.1      | 0.2                 |

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 22                    | Nikon     |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 19.6               | 18.9               | 19.3                  | 0.0193                | 1501.3    | 14.7                |
| 2                | 19.0               | 19.3               | 19.2                  | 0.0192                | 1517.0    | 14.9                |
| 3                | 19.0               | 19.6               | 19.3                  | 0.0193                | 1493.5    | 14.6                |
| 4                | 19.3               | 19.3               | 19.3                  | 0.0193                | 1493.5    | 14.6                |
| 5                | 19.3               | 19.1               | 19.2                  | 0.0192                | 1509.1    | 14.8                |
| <b>Average</b>   | 19.2               | 19.2               | 19.2                  | 0.0192                | 1502.9    | 14.7                |
| <b>Std. dev.</b> | 0.3                | 0.3                | 0.1                   | 0.0001                | 10.2      | 0.1                 |

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 200                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 20.3               | 20.1               | 20.2                  | 0.0202                | 1363.4    | 13.4                |
| 2                | 20.4               | 20.2               | 20.3                  | 0.0203                | 1350.0    | 13.2                |
| 3                | 20.4               | 20.4               | 20.4                  | 0.0204                | 1336.8    | 13.1                |
| 4                | 20.1               | 20.2               | 20.2                  | 0.0202                | 1370.2    | 13.4                |
| 5                | 20.3               | 20.3               | 20.3                  | 0.0203                | 1350.0    | 13.2                |
| <b>Average</b>   | 20.3               | 20.2               | 20.3                  | 0.0203                | 1354.1    | 13.3                |
| <b>Std. dev.</b> | 0.1                | 0.1                | 0.1                   | 0.0001                | 13.0      | 0.1                 |

|                  | gf                 | N                  |                       | Temp<br>(°C)          |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 400                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 20.8               | 20.9               | 20.9                  | 0.0209                | 1279.7    | 12.6                |
| 2                | 21.1               | 21.2               | 21.2                  | 0.0212                | 1243.7    | 12.2                |
| 3                | 21.3               | 20.6               | 21.0                  | 0.0210                | 1267.5    | 12.4                |
| 4                | 20.7               | 20.8               | 20.8                  | 0.0208                | 1292.1    | 12.7                |
| 5                | 21.0               | 20.3               | 20.7                  | 0.0207                | 1304.6    | 12.8                |
| <b>Average</b>   | 21.0               | 20.8               | 20.9                  | 0.0209                | 1277.5    | 12.5                |
| <b>Std. dev.</b> | 0.2                | 0.3                | 0.2                   | 0.0002                | 23.4      | 0.2                 |

Table A-6.7. SN47; February 2004 (continued).

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 21.7       | 21.8       | 21.8          | 0.0218        | 1176.0 | 11.5        |
| 2         | 22.1       | 22.3       | 22.2          | 0.0222        | 1128.8 | 11.1        |
| 3         | 22.1       | 22.3       | 22.2          | 0.0222        | 1128.8 | 11.1        |
| 4         | 22.0       | 21.8       | 21.9          | 0.0219        | 1159.9 | 11.4        |
| 5         | 21.5       | 21.5       | 21.5          | 0.0215        | 1203.5 | 11.8        |
| Average   | 21.9       | 21.9       | 21.9          | 0.0219        | 1159.4 | 11.4        |
| Std. dev. | 0.3        | 0.4        | 0.3           | 0.0003        | 32.0   | 0.3         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 800           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 22.1       | 22.4       | 22.3          | 0.0223        | 1123.7 | 11.0        |
| 2         | 22.9       | 23.1       | 23.0          | 0.0230        | 1051.6 | 10.3        |
| 3         | 22.9       | 22.6       | 22.8          | 0.0228        | 1074.9 | 10.5        |
| 4         | 22.9       | 22.5       | 22.7          | 0.0227        | 1079.6 | 10.6        |
| 5         | 22.3       | 22.6       | 22.5          | 0.0225        | 1103.8 | 10.8        |
| Average   | 22.6       | 22.6       | 22.6          | 0.0226        | 1086.7 | 10.7        |
| Std. dev. | 0.4        | 0.3        | 0.3           | 0.0003        | 27.8   | 0.3         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 1000          |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 25.2       | 25.0       | 25.1          | 0.0251        | 883.0  | 8.7         |
| 2         | 24.8       | 25.0       | 24.9          | 0.0249        | 897.3  | 8.8         |
| 3         | 24.9       | 24.7       | 24.8          | 0.0248        | 904.5  | 8.9         |
| 4         | 24.5       | 24.6       | 24.6          | 0.0246        | 923.0  | 9.1         |
| 5         | 24.5       | 24.7       | 24.6          | 0.0246        | 919.3  | 9.0         |
| Average   | 24.8       | 24.8       | 24.8          | 0.0248        | 905.4  | 8.9         |
| Std. dev. | 0.3        | 0.2        | 0.2           | 0.0002        | 16.4   | 0.2         |

Table A-6.8. STK4; September 2002.

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 16.3       | 16.4       | 16.4          | 0.0164        | 2081.1 | 20.4        |
| 2         | 16.1       | 16.3       | 16.2          | 0.0162        | 2119.8 | 20.8        |
| 3         | 16.3       | 15.9       | 16.1          | 0.0161        | 2146.2 | 21.0        |
| 4         | 16.6       | 16.4       | 16.5          | 0.0165        | 2043.4 | 20.0        |
| 5         | 16.3       | 16.3       | 16.3          | 0.0163        | 2093.9 | 20.5        |
| Average   | 16.3       | 16.3       | 16.3          | 0.0163        | 2096.9 | 20.6        |
| Std. dev. | 0.2        | 0.2        | 0.2           | 0.0002        | 39.0   | 0.4         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 200           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 16.7       | 16.9       | 16.4          | 0.0164        | 2081.1 | 20.4        |
| 2         | 17.0       | 17.1       | 16.2          | 0.0162        | 2119.8 | 20.8        |
| 3         | 16.9       | 17.0       | 16.1          | 0.0161        | 2146.2 | 21.0        |
| 4         | 16.9       | 17.1       | 16.5          | 0.0165        | 2043.4 | 20.0        |
| 5         | 17.0       | 16.8       | 16.3          | 0.0163        | 2093.9 | 20.5        |
| Average   | 16.3       | 16.3       | 16.3          | 0.0163        | 2096.9 | 20.6        |
| Std. dev. | 0.2        | 0.2        | 0.2           | 0.0002        | 39.0   | 0.4         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 18.2       | 18.1       | 16.8          | 0.0168        | 1971.1 | 19.3        |
| 2         | 17.9       | 17.9       | 17.1          | 0.0171        | 1913.7 | 18.8        |
| 3         | 18.1       | 18.2       | 17.0          | 0.0170        | 1936.4 | 19.0        |
| 4         | 18.3       | 18.4       | 17.0          | 0.0170        | 1925.0 | 18.9        |
| 5         | 18.2       | 18.1       | 16.9          | 0.0169        | 1947.8 | 19.1        |
| Average   | 16.9       | 17.0       | 16.9          | 0.0169        | 1938.8 | 19.0        |
| Std. dev. | 0.1        | 0.1        | 0.1           | 0.0001        | 22.1   | 0.2         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 18.9       | 19.2       | 19.1          | 0.0191        | 1533.0 | 15.0        |
| 2         | 19.3       | 19.0       | 19.2          | 0.0192        | 1517.0 | 14.9        |
| 3         | 18.7       | 18.6       | 18.7          | 0.0187        | 1599.4 | 15.7        |
| 4         | 19.0       | 19.2       | 19.1          | 0.0191        | 1525.0 | 15.0        |
| 5         | 18.8       | 18.7       | 18.8          | 0.0188        | 1582.4 | 15.5        |
| Average   | 18.9       | 18.9       | 18.9          | 0.0189        | 1551.4 | 15.2        |
| Std. dev. | 0.2        | 0.3        | 0.2           | 0.0002        | 37.1   | 0.4         |



Table A-6.8. STK4; September 2002 (continued).

|                  | <b>gf</b>          | <b>N</b>           |                       | <b>Temp<br/>(°C)</b>  |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 800                   |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 19.8               | 19.3               | 19.6                  | 0.0196                | 1455.6    | 14.3                |
| 2                | 19.2               | 19.3               | 19.3                  | 0.0193                | 1501.3    | 14.7                |
| 3                | 19.0               | 19.4               | 19.2                  | 0.0192                | 1509.1    | 14.8                |
| 4                | 19.2               | 19.0               | 19.1                  | 0.0191                | 1525.0    | 15.0                |
| 5                | 19.3               | 19.2               | 19.3                  | 0.0193                | 1501.3    | 14.7                |
| <b>Average</b>   | 19.3               | 19.2               | 19.3                  | 0.0193                | 1498.4    | 14.7                |
| <b>Std. dev.</b> | 0.3                | 0.2                | 0.2                   | 0.0002                | 25.8      | 0.3                 |

Table A-6.9. STK4; February 2004.

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            | Leco   |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 16.8       | 16.9       | 16.9          | 0.0169        | 1959.4 | 19.2        |
| 2         | 16.4       | 16.8       | 16.6          | 0.0166        | 2018.9 | 19.8        |
| 3         | 16.9       | 16.9       | 16.9          | 0.0169        | 1947.8 | 19.1        |
| 4         | 17.1       | 16.7       | 16.9          | 0.0169        | 1947.8 | 19.1        |
| 5         | 16.9       | 16.9       | 16.9          | 0.0169        | 1947.8 | 19.1        |
| Average   | 16.8       | 16.8       | 16.8          | 0.0168        | 1964.4 | 19.3        |
| Std. dev. | 0.3        | 0.1        | 0.1           | 0.0001        | 30.9   | 0.3         |

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            | Nikon  |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 16.5       | 16.5       | 16.5          | 0.0165        | 2043.4 | 20.0        |
| 2         | 16.7       | 16.4       | 16.6          | 0.0166        | 2031.1 | 19.9        |
| 3         | 17.4       | 16.4       | 16.9          | 0.0169        | 1947.8 | 19.1        |
| 4         | 16.6       | 16.1       | 16.4          | 0.0164        | 2081.1 | 20.4        |
| 5         | 16.7       | 16.5       | 16.6          | 0.0166        | 2018.9 | 19.8        |
| Average   | 16.8       | 16.4       | 16.6          | 0.0166        | 2024.5 | 19.9        |
| Std. dev. | 0.4        | 0.2        | 0.2           | 0.0002        | 48.8   | 0.5         |

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 200           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 17.5       | 17.3       | 17.4          | 0.0174        | 1837.5 | 18.0        |
| 2         | 17.3       | 17.0       | 17.2          | 0.0172        | 1891.5 | 18.5        |
| 3         | 18.1       | 17.8       | 18.0          | 0.0180        | 1726.6 | 16.9        |
| 4         | 17.6       | 17.1       | 17.4          | 0.0174        | 1848.1 | 18.1        |
| 5         | 17.5       | 17.3       | 17.4          | 0.0174        | 1837.5 | 18.0        |
| 6         | 17.7       | 17.1       | 17.4          | 0.0174        | 1837.5 | 18.0        |
| Average   | 17.6       | 17.3       | 17.4          | 0.0174        | 1829.8 | 17.9        |
| Std. dev. | 0.3        | 0.3        | 0.3           | 0.0003        | 54.7   | 0.5         |

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 18.8       | 18.0       | 18.4          | 0.0184        | 1643.2 | 16.1        |
| 2         | 18.2       | 18.4       | 18.3          | 0.0183        | 1661.2 | 16.3        |
| 3         | 18.7       | 18.7       | 18.7          | 0.0187        | 1590.9 | 15.6        |
| 4         | 18.2       | 18.4       | 18.3          | 0.0183        | 1661.2 | 16.3        |
| 5         | 19.1       | 18.7       | 18.9          | 0.0189        | 1557.4 | 15.3        |
| 6         | 18.6       | 18.7       | 18.7          | 0.0187        | 1599.4 | 15.7        |
| Average   | 18.6       | 18.5       | 18.5          | 0.0185        | 1618.9 | 15.9        |
| Std. dev. | 0.4        | 0.3        | 0.2           | 0.0002        | 42.7   | 0.4         |

Table A-6.9. STK4; February 2004 (continued).

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 19.1       | 18.8       | 19.0          | 0.0190        | 1549.2 | 15.2        |
| 2         | 19.7       | 19.0       | 19.4          | 0.0194        | 1485.8 | 14.6        |
| 3         | 19.2       | 18.5       | 18.9          | 0.0189        | 1565.7 | 15.4        |
| 4         | 19.7       | 19.3       | 19.5          | 0.0195        | 1463.0 | 14.3        |
| 5         | 19.5       | 18.8       | 19.2          | 0.0192        | 1517.0 | 14.9        |
| 6         | 19.6       | 19.6       | 19.6          | 0.0196        | 1448.1 | 14.2        |
| Average   | 19.5       | 19.0       | 19.2          | 0.0192        | 1504.8 | 14.8        |
| Std. dev. | 0.3        | 0.4        | 0.3           | 0.0003        | 47.2   | 0.5         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 800           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 19.9       | 19.6       | 19.8          | 0.0198        | 1426.2 | 14.0        |
| 2         | 20.4       | 19.7       | 20.1          | 0.0201        | 1383.9 | 13.6        |
| 3         | 20.1       | 19.6       | 19.9          | 0.0199        | 1411.9 | 13.8        |
| 4         | 19.8       | 20.1       | 20.0          | 0.0200        | 1397.8 | 13.7        |
| 5         | 20.2       | 19.9       | 20.1          | 0.0201        | 1383.9 | 13.6        |
| 6         | 20.2       | 19.8       | 20.0          | 0.0200        | 1390.8 | 13.6        |
| Average   | 20.1       | 19.8       | 19.9          | 0.0199        | 1400.7 | 13.7        |
| Std. dev. | 0.2        | 0.2        | 0.1           | 0.0001        | 18.4   | 0.2         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 1000          |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 21.2       | 20.4       | 20.8          | 0.0208        | 1285.9 | 12.6        |
| 2         | 20.9       | 20.6       | 20.8          | 0.0208        | 1292.1 | 12.7        |
| 3         | 21.2       | 20.6       | 20.9          | 0.0209        | 1273.6 | 12.5        |
| 4         | 20.9       | 20.6       | 20.8          | 0.0208        | 1292.1 | 12.7        |
| 5         | 21.0       | 21.0       | 21.0          | 0.0210        | 1261.5 | 12.4        |
| Average   | 21.0       | 20.6       | 20.8          | 0.0208        | 1281.0 | 12.6        |
| Std. dev. | 0.2        | 0.2        | 0.1           | 0.0001        | 13.3   | 0.1         |

Table A-6.10. SN5P; February 2004.

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 22            | Leco   |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 20.1       | 19.6       | 19.9          | 0.0199        | 1411.9 | 13.8        |
| 2         | 20.3       | 20.3       | 20.3          | 0.0203        | 1350.0 | 13.2        |
| 3         | 19.7       | 19.6       | 19.7          | 0.0197        | 1440.8 | 14.1        |
| 4         | 19.3       | 19.3       | 19.3          | 0.0193        | 1493.5 | 14.6        |
| 5         | 20.4       | 20.4       | 20.4          | 0.0204        | 1336.8 | 13.1        |
| Average   | 20.0       | 19.8       | 19.9          | 0.0199        | 1406.6 | 13.8        |
| Std. dev. | 0.5        | 0.5        | 0.5           | 0.0005        | 64.9   | 0.6         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 22            | Nikon  |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 19.9       | 19.9       | 19.9          | 0.0199        | 1404.8 | 13.8        |
| 2         | 20.2       | 20.2       | 20.2          | 0.0202        | 1363.4 | 13.4        |
| 3         | 20.6       | 20.4       | 20.5          | 0.0205        | 1323.8 | 13.0        |
| 4         | 20.1       | 19.6       | 19.9          | 0.0199        | 1411.9 | 13.8        |
| 5         | 20.0       | 19.4       | 19.7          | 0.0197        | 1433.5 | 14.1        |
| Average   | 20.2       | 19.9       | 20.0          | 0.0200        | 1387.5 | 13.6        |
| Std. dev. | 0.3        | 0.4        | 0.3           | 0.0003        | 43.7   | 0.4         |
|           |            |            |               |               |        |             |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 200           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 20.0       | 20.1       | 20.1          | 0.0201        | 1383.9 | 13.6        |
| 2         | 20.5       | 20.6       | 20.6          | 0.0206        | 1317.3 | 12.9        |
| 3         | 21.4       | 20.8       | 21.1          | 0.0211        | 1249.6 | 12.3        |
| 4         | 20.7       | 21.2       | 21.0          | 0.0210        | 1267.5 | 12.4        |
| 5         | 21.0       | 20.6       | 20.8          | 0.0208        | 1285.9 | 12.6        |
| 6         | 21.1       | 21.3       | 21.2          | 0.0212        | 1237.8 | 12.1        |
| 7         | 21.8       | 21.8       | 21.8          | 0.0218        | 1170.6 | 11.5        |
| 8         | 21.4       | 21.4       | 21.4          | 0.0214        | 1214.8 | 11.9        |
| 9         | 20.9       | 20.9       | 20.9          | 0.0209        | 1273.6 | 12.5        |
| 10        | 20.6       | 21.5       | 21.1          | 0.0211        | 1255.5 | 12.3        |
| Average   | 20.9       | 21.0       | 21.0          | 0.0210        | 1265.6 | 12.4        |
| Std. dev. | 0.5        | 0.5        | 0.5           | 0.0005        | 57.6   | 0.6         |

Table A-6.10. SN5P; February 2004 (continued).

|           | gf         | N          |               | Temp<br>(°C)  |        |             |
|-----------|------------|------------|---------------|---------------|--------|-------------|
| Load =    | 300        | 2.9421     |               | 400           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 21.1       | 21.6       | 21.4          | 0.0214        | 1220.5 | 12.0        |
| 2         | 21.6       | 21.3       | 21.5          | 0.0215        | 1209.1 | 11.9        |
| 3         | 21.5       | 22.0       | 21.8          | 0.0218        | 1176.0 | 11.5        |
| 4         | 21.7       | 21.8       | 21.8          | 0.0218        | 1176.0 | 11.5        |
| 5         | 22.2       | 22.2       | 22.2          | 0.0222        | 1128.8 | 11.1        |
| Average   | 21.6       | 21.8       | 21.7          | 0.0217        | 1182.1 | 11.6        |
| Std. dev. | 0.4        | 0.3        | 0.3           | 0.0003        | 35.8   | 0.4         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 600           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 23.4       | 23.4       | 23.4          | 0.0234        | 1016.0 | 10.0        |
| 2         | 23.5       | 24.3       | 23.9          | 0.0239        | 973.9  | 9.6         |
| 3         | 22.7       | 24.3       | 23.5          | 0.0235        | 1007.4 | 9.9         |
| 4         | 23.6       | 23.4       | 23.5          | 0.0235        | 1007.4 | 9.9         |
| 5         | 22.3       | 23.3       | 22.8          | 0.0228        | 1070.2 | 10.5        |
| Average   | 23.1       | 23.7       | 23.4          | 0.0234        | 1015.0 | 10.0        |
| Std. dev. | 0.6        | 0.5        | 0.4           | 0.0004        | 34.8   | 0.3         |
|           | gf         | N          |               | Temp<br>(°C)  |        |             |
| Load =    | 300        | 2.9421     |               | 800           |        |             |
| Indent #  | d1<br>(μm) | d2<br>(μm) | Ave d<br>(μm) | Ave d<br>(mm) | HV     | HV<br>(GPa) |
| 1         | 24.6       | 25.0       | 24.8          | 0.0248        | 904.5  | 8.9         |
| 2         | 24.9       | 25.3       | 25.1          | 0.0251        | 883.0  | 8.7         |
| 3         | 25.3       | 25.4       | 25.4          | 0.0254        | 865.7  | 8.5         |
| 4         | 23.4       | 23.9       | 23.7          | 0.0237        | 994.6  | 9.8         |
| 5         | 24.0       | 24.2       | 24.1          | 0.0241        | 957.8  | 9.4         |
| Average   | 24.4       | 24.8       | 24.6          | 0.0246        | 921.1  | 9.0         |
| Std. dev. | 0.8        | 0.7        | 0.7           | 0.0007        | 53.7   | 0.5         |

Table A-6.10. SN5P; February 2004 (continued).

|                  | <b>gf</b>          | <b>N</b>           |                       | <b>Temp<br/>(°C)</b>  |           |                     |
|------------------|--------------------|--------------------|-----------------------|-----------------------|-----------|---------------------|
| <b>Load =</b>    | 300                | 2.9421             |                       | 1000                  |           |                     |
| <b>Indent #</b>  | <b>d1<br/>(μm)</b> | <b>d2<br/>(μm)</b> | <b>Ave d<br/>(μm)</b> | <b>Ave d<br/>(mm)</b> | <b>HV</b> | <b>HV<br/>(GPa)</b> |
| 1                | 26.5               | 25.9               | 26.2                  | 0.0262                | 810.4     | 7.9                 |
| 2                | 27.0               | 25.9               | 26.5                  | 0.0265                | 795.2     | 7.8                 |
| 3                | 26.8               | 26.0               | 26.4                  | 0.0264                | 798.2     | 7.8                 |
| 4                | 26.1               | 25.8               | 26.0                  | 0.0260                | 826.1     | 8.1                 |
| 5                | 25.5               | 26.6               | 26.1                  | 0.0261                | 819.8     | 8.0                 |
| <b>Average</b>   | 26.4               | 26.0               | 26.2                  | 0.0262                | 810.0     | 7.9                 |
| <b>Std. dev.</b> | 0.6                | 0.3                | 0.2                   | 0.0002                | 13.4      | 0.1                 |

## Appendix B. Thermal Properties

Table B-1. Thermal conductivity and heat capacity data between room temperature and 1000 °C.

| Sample | Thickness (mm) | r @ 25 °C (g/cm <sup>3</sup> ) | Temperature (°C) | Specific Heat (c <sub>p</sub> ) (J/g-K) | Diffusivity (a) (cm <sup>2</sup> /s) | Conductivity (l) (W/m-K) |
|--------|----------------|--------------------------------|------------------|---|--------------------------------------|--------------------------|
| ALOX   | 2.01           | 3.88                           | 25               | 0.788                                   | 0.103                                | 31.4                     |
|        | 2.01           | 3.87                           | 150              | 0.984                                   | 0.0548                               | 20.9                     |
|        | 2.01           | 3.86                           | 300              | 1.12                                    | 0.0352                               | 15.2                     |
|        | 2.02           | 3.83                           | 600              | 1.22                                    | 0.0218                               | 10.2                     |
|        | 2.03           | 3.79                           | 1000             | 1.30                                    | 0.0147                               | 7.20                     |
| ZR02   | 2.03           | 6.11                           | 25               | 0.462                                   | 0.0111                               | 3.13                     |
|        | 2.04           | 6.09                           | 150              | 0.529                                   | 0.00889                              | 2.87                     |
|        | 2.04           | 6.06                           | 300              | 0.566                                   | 0.00777                              | 2.66                     |
|        | 2.05           | 5.99                           | 600              | 0.607                                   | 0.00648                              | 2.36                     |
|        | 2.06           | 5.91                           | 1000             | 0.640                                   | 0.00585                              | 2.21                     |
| SCEH   | 2.11           | 3.16                           | 25               | 0.719                                   | 0.748                                | 170                      |
|        | 2.11           | 3.15                           | 150              | 0.904                                   | 0.456                                | 130                      |
|        | 2.11           | 3.15                           | 300              | 1.05                                    | 0.300                                | 98.9                     |
|        | 2.11           | 3.13                           | 600              | 1.18                                    | 0.179                                | 66.1                     |
|        | 2.12           | 3.11                           | 1000             | 1.25                                    | 0.116                                | 45.2                     |
| SCLH   | 2.11           | 3.09                           | 25               | 0.733                                   | 0.3298                               | 74.6                     |
|        | 2.11           | 3.08                           | 150              | 0.915                                   | 0.2378                               | 67.1                     |
|        | 2.11           | 3.08                           | 300              | 1.05                                    | 0.1812                               | 58.6                     |
|        | 2.11           | 3.06                           | 600              | 1.18                                    | 0.1225                               | 44.4                     |
|        | 2.12           | 3.04                           | 1000             | 1.27                                    | 0.0861                               | 33.2                     |
| SC46   | 2.03           | 3.10                           | 25               | 0.696                                   | 0.463                                | 99.9                     |
|        | 2.03           | 3.10                           | 150              | 0.902                                   | 0.296                                | 82.8                     |
|        | 2.04           | 3.09                           | 300              | 1.05                                    | 0.220                                | 71.4                     |
|        | 2.04           | 3.08                           | 600              | 1.18                                    | 0.138                                | 50.3                     |
|        | 2.04           | 3.06                           | 1000             | 1.28                                    | 0.0951                               | 37.3                     |
| SN47   | 2.03           | 3.20                           | 25               | 0.690                                   | 0.120                                | 26.5                     |
|        | 2.03           | 3.20                           | 150              | 0.887                                   | 0.0839                               | 23.8                     |
|        | 2.04           | 3.19                           | 300              | 1.03                                    | 0.0644                               | 21.3                     |
|        | 2.04           | 3.18                           | 600              | 1.17                                    | 0.0462                               | 17.2                     |
|        | 2.04           | 3.17                           | 1000             | 1.27                                    | 0.0350                               | 14.1                     |

Table B-1. Thermal conductivity and heat capacity data between room temperature and 1000 °C (continued).

| Sample | Thickness (mm) | r @ 25 °C (g/cm <sup>3</sup> ) | Temperature (°C) | Specific Heat (c <sub>p</sub> ) (J/g-K) | Diffusivity (a) (cm <sup>2</sup> /s) | Conductivity (l) (W/m-K) |
|--------|----------------|--------------------------------|------------------|---|--------------------------------------|--------------------------|
| STK4   | 2.11           | 3.36                           | 25               | 0.736                                   | 0.0438                               | 10.8                     |
|        | 2.11           | 3.36                           | 150              | 0.916                                   | 0.0329                               | 10.1                     |
|        | 2.11           | 3.35                           | 300              | 1.05                                    | 0.0272                               | 9.61                     |
|        | 2.11           | 3.34                           | 600              | 1.17                                    | 0.0225                               | 8.81                     |
|        | 2.11           | 3.33                           | 1000             | 1.24                                    | 0.0205                               | 8.49                     |
| SN5P   | 2.08           | 3.24                           | 25               | 0.695                                   | 0.143                                | 32.2                     |
|        | —              | —                              | 150              | 0.863                                   | 0.102                                | 28.4                     |
|        | —              | —                              | 300              | 1.00                                    | 0.0770                               | 24.9                     |
|        | —              | —                              | 600              | 1.14                                    | 0.0538                               | 19.9                     |
|        | —              | —                              | 1000             | 1.25                                    | 0.0397                               | 16.1                     |

Table B-2. Instantaneous coefficient of thermal expansion as a function of temperature (units =  $\times 10^{-6}/^{\circ}\text{C} = \text{ppm}/^{\circ}\text{C}$ ).

| Temp (°C) | Material |      |      |      |      |      |     |      |
|-----------|----------|------|------|------|------|------|-----|------|
|           | ALOX     | SCEH | SCLH | SC46 | SN47 | SN5P | TK4 | ZRO2 |
| 50        | 6.0      | 2.4  | 2.8  | 3.0  | 1.5  | 1.6  | 1.5 | 10.5 |
| 100       | 6.7      | 2.9  | 3.4  | 3.5  | 1.9  | 1.9  | 2.0 | 11.1 |
| 200       | 7.4      | 3.4  | 4.4  | 4.2  | 2.4  | 2.2  | 2.4 | 11.2 |
| 300       | 8.0      | 3.8  | 4.0  | 4.6  | 2.9  | 2.9  | 2.7 | 11.2 |
| 400       | 8.4      | 5.3  | 4.7  | 4.9  | 3.3  | 3.2  | 2.8 | 12.2 |
| 500       | 8.8      | 5.5  | 5.0  | 5.3  | 3.4  | 3.7  | 3.1 | 11.9 |
| 600       | 9.0      | 6.2  | 5.1  | 5.3  | 3.6  | 3.8  | 3.1 | 12.0 |
| 700       | 9.3      | 5.5  | 5.6  | 5.4  | 3.7  | 3.9  | 3.0 | 12.1 |
| 800       | 9.4      | 5.3  | 5.7  | 5.7  | 3.6  | 4.0  | 3.7 | 12.1 |
| 900       | 9.6      | 5.4  | 5.5  | 5.8  | 3.9  | 4.2  | 4.2 | 11.9 |
| 1000      | 9.4      | 5.6  | 5.5  | 5.7  | 3.5  | 4.9  | 4.6 | 11.9 |



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T LI  
2800 POWDER MILL RD  
ADELPHI MD 20783-1197

NO. OF  
COPIES ORGANIZATION

B POWERS  
D SNOHA  
J SOUTH  
M STAKER  
J SWAB  
J TZENG  
AMSRD ARL WM MC  
M MAHER  
AMSRD ARL WM MD  
W ROY  
AMSRD ARL WM T  
B BURNS  
AMSRD ARL WM TA  
C HOPPEL

ABERDEEN PROVING GROUND

1 US ARMY ATC  
CSTE DTC AT AC I  
W C FRAZER  
400 COLLERAN RD  
APG MD 21005-5059

30 DIR USARL  
AMSRD ARL CI  
AMSRD ARL O AP EG  
M ADAMSON  
AMSRD ARL WM  
A HORST  
AMSRD ARL WM BD  
P CONROY  
C LEVERITT  
AMSRD ARL WM M  
B FINK  
J MCCAULEY  
AMSRD ARL WM MA  
S MCKNIGHT  
AMSRD ARL WM MB  
J BENDER  
T BOGETTI  
L BURTON  
R CARTER  
K CHO  
W DE ROSSET  
R DOWDING  
W DRYSDALE  
R EMERSON  
D HOPKINS  
R KASTE  
L KECSKES